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GEOMORPHOLOGY OF THE MIDDLE MISSISSIPPI RIVER

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20. ABSTRACT (Continued).

modifications in the [illegible] Mississippi River [illegible] the form and behavior of the river. [illegible] tions, the surface area of the [illegible] produce [illegible] maximum [illegible] increase [illegible] in the last [illegible] years. At the [illegible] distance [illegible] the [illegible] water [illegible] were [illegible]. It was concluded [illegible] be increased [illegible]. It is also possible to realign the river [illegible] very little sediment. However, this would require [illegible] of the main channel [illegible] extremely expensive [illegible] extending the [illegible] in the proper position [illegible] line.

PREFACE

The work described in this report was performed under Contract DACW39-73-C-0026, titled "Geomorphology of the Middle Mississippi River," dated October 1972, between the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and the Hydraulics Laboratory, Colorado State University, Ft. Collins, Colorado.

The report is a study of the geomorphological aspects of reducing the river widths to obtain a navigation channel and the physical impacts of river contraction works on the side channels along the Middle Mississippi River. The report was prepared by Dr. D. B. Simons, Associate Dean, Engineering Research Center, Dr. S. A. Schumm, Professor of Geology, and Dr. M. A. Stevens, Associate Professor of Civil Engineering, Colorado State University.

The contract was monitored by William P. Emge under the general supervision of Dr. John Harrison, Chief, Office for Environmental Studies, WES. Contracting officers were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE.

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INTRODUCTION

> "An enormous ditch, sometimes two or three miles wide, running liquid mud, six miles per hour: its strong and frothy current choked and obstructed everywhere by huge logs and whole forest trees..."

These are the words with which Charles Dickens described the Mississippi River in 1842. They were the only kind words that Dickens had for the Father of Rivers and for those who were the first aliens to inhabit her banks. Traveling by steamboat from Louisville to St. Louis, Dickens wrote:

> "...we arrived at a spot so much more desolate than any we had yet beheld, that the forlornest places we had passed were, in comparison with it, full of interest. At the junction of the two rivers, on ground so flat and low and marshy, that at certain seasons of the year it is inundated to the housetops, lies a breeding-place of fever , ague, and death; vaunted in England as a mine of Golden Hope, and speculated in, on the faith of monstrous representations, to many people's ruin. A dismal swamp, on which the half-built houses rot away: cleared here and there for the space of a few yards; and teeming, then, with rank, unwholesome vegetation, in whose baleful shade the wretched wanderers who are tempted hither droop, and die, and lay their bones; the hateful Mississippi circling and eddying before it, and turning off upon its southern course, a slimy monster hideous to behold; a hotbed of disease, an ugly sepulchre, a grave uncheered by any gleam of promise: a place without one single quality, in earth or air or water, to commend it: such is this dismal Cairo."

In contrast Mark Twain employed the words "remarkable," "prosperous," "romance," and "beauty" to describe the same scenes that Dickens saw. The scenes were those of the Middle Mississippi River.

Without deference to Twain, those who lived along and on the river in the 19th century were not, as a whole, happy with the behavior of the natural river. Navigation on the natural river was extremely hazardous and people living within the floodplain were subject to frequent floods; therefore, they petitioned the Federal Government to provide a more navigable waterway and flood protective works. This work has been very successful to this point in time.

Stated simply, the objectives of developments along the Middle Mississippi River have been to provide flood protection to people and property on the floodplain and to provide a suitable channel for navigation. The river has been contracted to provide the navigation channel, and it has been leveed to protect the people and property from floods.

This program was initiated at a time in our nation's history when little consideration was given to the overall impact to the natural environment. Studies are now under way to determine some of the environmental impacts which have occurred as a result of the physical changes necessary to provide flood protection works and develop and maintain a 9-ft navigation channel. Some of the major impacts are alterations of fish and wildlife habitat, and alterations of river discharges and the corresponding stages. The impact of both dikes and levees on flood stages are discussed in this report. Trends in river behavior that are identified can be evaluated and incorporated into present and future river development considering such major issues as flood control, navigation and environmental impact.

In 1927, the Corps of Engineers was authorized by Congress to obtain and maintain a 9-foot deep, 300-ft wide channel for navigation through the Middle Mississippi River. This channel depth has been difficult to obtain [Degenhardt, 1973] especially in areas where the main river flow crosses from one bank to the other. Adequate depths in troublesome channel crossings have been maintained by dredging. Dredging is only a temporary solution because the dredged sections generally fill again with sediments. A permanent 9-foot deep channel can be obtained throughout most of the river by further reducing the river width.

A cooperative research team has been assembled to perform an environmental inventory and to study the environmental effects of further decreasing the river width to obtain the authorized navigation channel. The cooperating agencies are: the U.S. Army Engineer District, St. Louis, Mo.; the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.; Southern Illinois University at Carbondale; Missouri Department of Conservation; Illinois Department of Conservation; Illinois Natural History survey; and Colorado State University.

At Colorado State University, we have been studying the geomorphological aspects of reducing the river widths to obtain a navigation channel. Specifically we are concerned with the physical impact of river contraction works on the side channels along the Middle Mississippi River. The side channels provide a different and possibly more favorable habitat for biota than the main river channel. The side channels may be essential in order to maintain the diversity of biota in the river. Hence, one of our objectives was to determine if future works to improve navigation in the river could be designed to maintain or improve those side channel environments that may be favorable to fish and wildlife. Studies of the life history of side channels in terms of river flows, sediment transport and growths of vegetation have been made by Colorado State University to provide a basis for evaluation of the physical changes in the river system. The studies include physical model studies of side channels conducted in the Hydraulics Laboratory at Colorado State University. The subsequent environmental impact of these physical changes will be evaluated by other agencies on the cooperative research team.

We are concerned also with the combined effects of navigation improvement structures and flood protection works on flood stages. Last year, 1973, the maximum flood stage of record occurred at St. Louis. The record high-water level occurred in conjunction with a 15-year frequency flood; a flood flow nearly 500,000 cfs smaller than the flood discharge of record. Congressionally authorized improvements of the Mississippi River for navigation and flood protection have resulted in higher water levels for smaller flood discharges.

In order to ascertain how developments are changing the river morphology and behavior, the form and behavior of the river in its natural or undeveloped state have been studied. Herein, the history of development and modification of the Middle Mississippi River is reviewed. In general the river was unaffected by developments prior to the twentieth centry. Thereafter, flood protective works (mainline levees) were constructed which eliminated flood water from reaching most of the former floodplain. Dikes were built to obtain and maintain a navigable 9-foot channel at low flow. The levee system is completed and was a major factor in negating flood damages in the Middle Mississippi River in 1973. The dike fields are still being constructed and maintained to obtain a 9-foot channel. Therefore, the nineteenth century river is considered as "natural" and the twentieth century as "developed."

Once this division into "natural" and "developed" time periods was established, we could easily describe how the Mississippi River has geomorphically and hydraulically responded to development. In fact, there are more data available than can be used in the time span of this study. We have focused on the channel position riverbed area, water and sediment flows, stages, cross-sectional area, channel bed elevations, and the stage versus discharge relation for the Middle Mississippi River. The variations in channel position, riverbed areas, cross-sectional areas, and channel bed elevations describe how the river morphology has been changing. The variations in water and sediment flows, stages, and stage versus discharge indicate how the river behavior is changing.

Side channels along the Middle Mississippi are of two types; those formed naturally and those formed in the dike fields used to contract the river. Most side channels are being filled with sediments carried by the river. The rates of filling are variable. No new natural side channels are being formed and it is anticipated that very few man-made side channels will result from future contractions of the Middle Mississippi River.

DEVELOPMENTS IN THE MIDDLE MISSISSIPPI

The objectives of developments along the Mississippi River have been to provide flood protection to people and property on the floodplain and to provide enough depth of water for commercial transport during times of low-water flow.

In the 195-mile reach of river between the mouth of the Missouri River above St. Louis to the mouth of the Ohio River at Cairo, the Mississippi River is known as the Middle Mississippi (Fig. 1). This reach is the hub of an interconnected inland river system serving the eastern, midwest and central plains regions of the United States. The hub has been a troublesome section of river for some time. Mark Twain wrote of the St. Louis to Cairo section

> "and the Mississippi changes its channel so constantly that the pilots used to always find it necessary to run down to Cairo to take a fresh look, when their boats were to lie in port for a week; that is, when the water was at a low state."

The first undertakings to improve conditions on the Middle Mississippi River were to remove snags (sunken debris such as trees) hazardous to navigation between New Orleans and the Missouri River [Maher, 1964]. This work to be done by the Corps of Engineers, was authorized by Congress in May 1824. In the intervening years between 1824 and 1881, private land owners constructed some low-level levees along the river banks to prevent the flooding of their rich floodplain land. On March 31, 1881, a comprehensive plan for regulation of the Middle Mississippi River was approved by Congress. The plan called for the continuous improvement of the navigation channel by reducing the width of the river to 2500 feet. The Corps of Engineers started the work at St. Louis and continued downstream with construction of revetments and permeable dikes.

In 1879 the Illinois State Drainage and Levee Act was passed which cleared the way for organized levee districts to accomplish the needed works with the aid of state funds. However, in the Middle Mississippi, levee construction was not intensive until 1907.

The Corps of Engineers became involved in the supervision of navigable streams under the terms of the 1928 Flood Control Act. Initially the Federal government's interest was in evaluating the degree of protection provided by the levee districts. Congress had authorized funds for the development of a minimum 9-foot deep, 300-foot wide navigation channel in the Middle Mississippi. A major portion of the channel improvements for navigation were constructed between 1927 and 1944 [Maher, 1963].

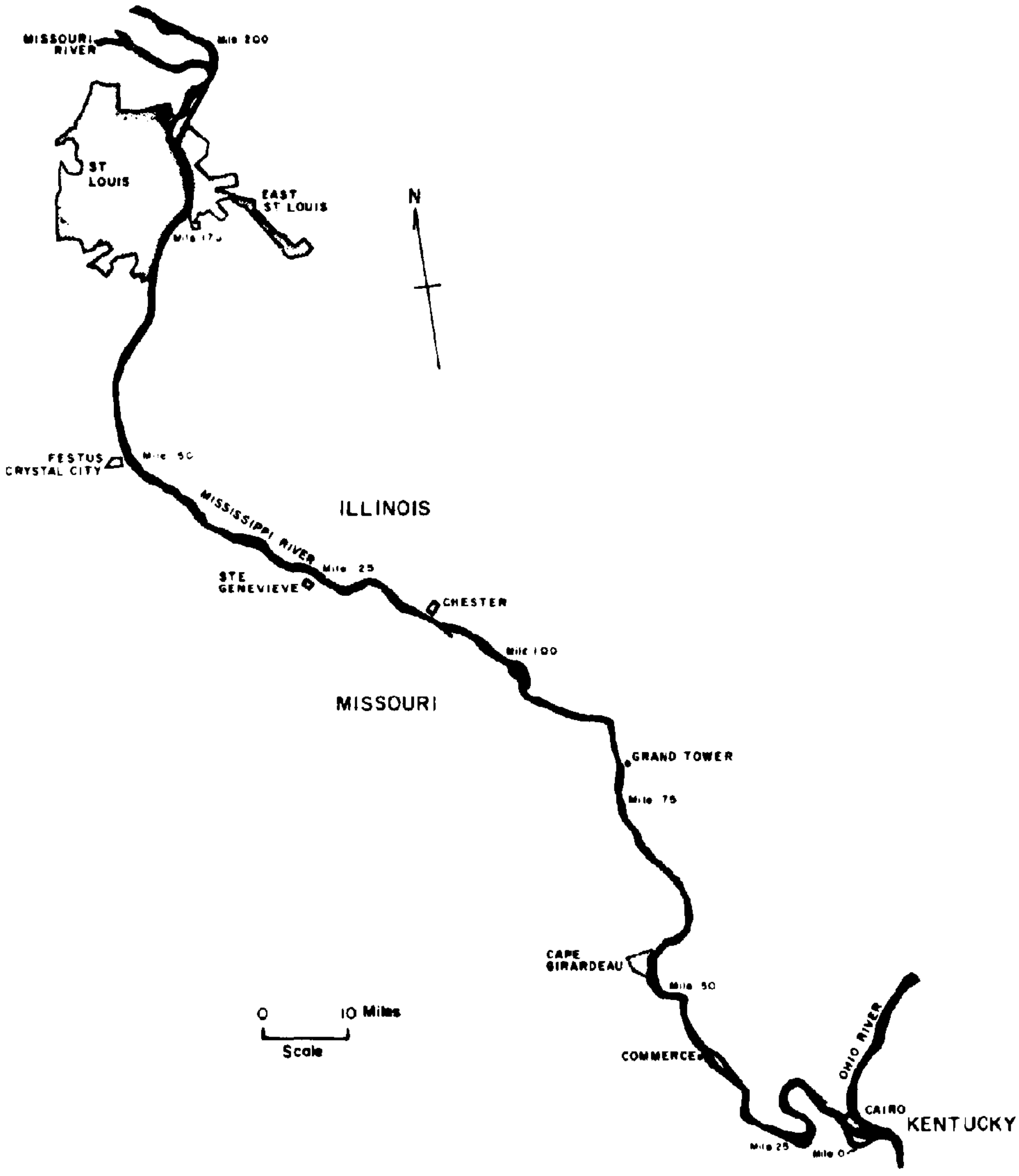


FIGURE 1 MAP OF THE MIDDLE MISSISSIPPI RIVER

In 1973, almost the entire river between the mouth of the Missouri River north of St. Louis to Thebes Gap south of Cape Girardeau is lined with Corps of Engineers mainline levees on one bank or the other. (See Fig. 1). One hundred and twenty-two miles of bank-line revetment prevent the river from eating into floodplain properties [Degenhardt, 1973]. Over 800 dikes having a length of 91 miles have been projected out from the river banks into the river channel. The location of the dikes in a 16-mile reach of Middle Mississippi River is shown in Fig. 2.

At present, work continues by the Corps of Engineers to obtain and maintain a minimum 9-foot navigation channel between St. Louis and Cairo by extending the dikes so that the distance between the ends of dikes on opposite sides of the river is 1500 feet.

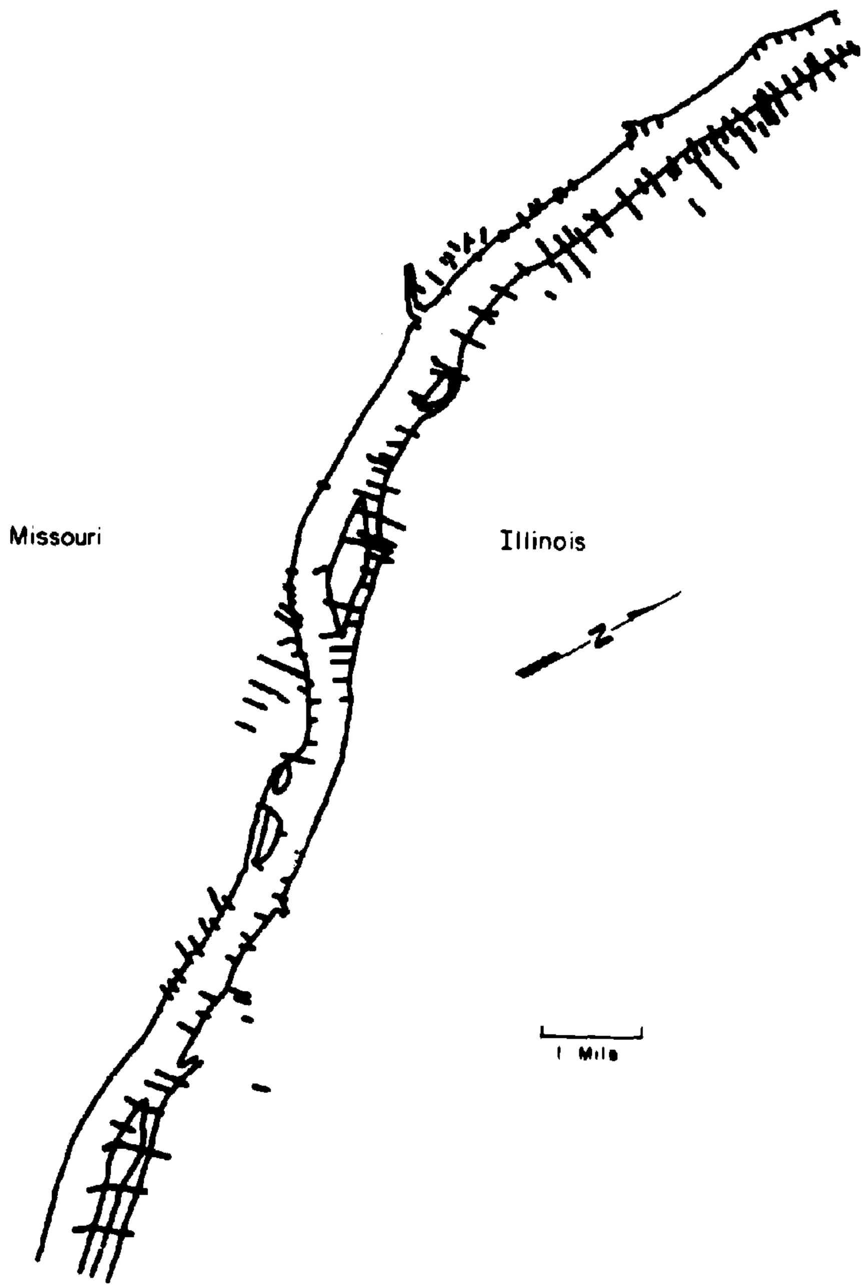


FIGURE 2 DIKES IN 1970--MILES 138 TO 154
[after Degenhardt, 1973]

EFFECTS OF DEVELOPMENTS

In this century of development the Mississippi River has been, according to Rhodes [1972],

> "dammed, leveed, jettied and polluted 'til Huck Finn himself wouldn't recognize it."

The levees were to provide the flood protection. The navigation dams and jetties were to establish a minimum depth of water for year-round navigation.

The objectives of flood protection and year-around river navigation have been met to a great extent in the Middle Mississippi River. However, the developments for flood protection and river navigation have produced a new river morphology and a different river behavior. The history of channel positions, riverbed areas, cross-sectional areas and channel bed elevations describes how the river morphology has been changing. The variations in water and sediment discharge, stages, and stage versus discharge indicate how the river behavior has been changing.

POSITION OF THE RIVER

The Middle Mississippi River has been well behaved in comparison to its neighbors, the Missouri River to the north and the Lower Mississippi to the south. The Middle Mississippi River has maintained a position along the western bluff line of the valley for all but a few miles between St. Louis and Thebes Gap. The entire floodplain to the east has not been affected by serious encroachments of the main channel. In this reach the river has shown no obvious tendency to meander.

We have no satisfactory answer as to why the river has chosen a course along the western bluff line. Speculation is that uplift due to the rebound from glacial loading over the Great Lakes provides sufficient lateral slope to keep the river on the west side for the last few centuries.

Large alluvial rivers, such as the Middle Mississippi, have the capability of rapid lateral movement. The scars on the floodplain attest to the fact that the river has been mobile in the past. The lateral movement is accomplished by bank erosion and bank caving at one side, and deposition in the form of bars in the channel on the other side. However, in the Middle Mississippi the channel position has been stable for the last two centuries. The position and sizes of the islands within the channel have changed with time.

Bank-line maps of the Middle Mississippi River in 1880 and in 1968 are compiled in Appendix A. The change in the bank-line positions can be obtained by matching the gridlines and comparing positions of the bank lines.

The migrations of the Middle Mississippi River appear very modest in comparison with other alluvial rivers. For those who live along the river this modest movement takes on more importance. The capture of part of the Kaskaskia River by the Mississippi River in 1881 was one example. A migrating meander loop of the Mississippi cut into the Kaskaskia River at a point about 9 miles upstream of the confluence of the Kaskaskia and Mississippi Rivers. As the Kaskaskia route to the confluence was much shorter than the Mississippi route, the Mississippi waters chose the Kaskaskia channel. In a period of a few years the Kaskaskia channel had become the Mississippi channel and the former Mississippi channel had become filled with sediment.

There are two obvious factors which could rapidly change the position of the river in the Middle Mississippi reach--earthquakes and great floods. We have an appreciation of the flood factor, but the earthquake potential is not well known. In 1811 one of the most serious earthquakes recorded in the nation occurred in the New Madrid region of Missouri. In the next two years over 1800 separate quakes were recorded in the New Madrid region. We have not found reference to any effects these quakes had on the Middle Mississippi River, but the effects in the New Madrid area are well documented [Fuller, 1912]. Evidence of ground movements were apparent on ground surface. The earthquake potential of the Middle Mississippi River region may be important in considering river development plans. The occurence of a major earthquake could cause bank failures, slumping of dikes, landslides, mudflows and possibly alternations of the channel position.

SURFACE AREAS

Herein the surface area of a river is defined as that area between the vegetated river banks. The surface area includes the area of the islands. Islands are defined as the vegetated areas within the channel banks and are separated from the mainland by the main channel and side channels. The riverbed area is defined as the surface area less the area of the islands. A comparison of the surface areas of the Middle Mississippi River between 1821, 1888 and 1968 is most interesting.

The surface areas of the Middle Mississippi between Jefferson Barracks, Missouri and Cairo, Illinois are given in Table I for the years 1821, 1888 and 1968. The 1821 map is identified as the "Reconnaissance of the Mississippi and Ohio Rivers" made in the months of October, November and December 1821 under the direction of the Board of Engineers. The area identified as 1888 was taken from maps made under the direction of the Mississippi River Commission between 1876 and 1888. The 1968 maps were prepared from aerial photograph mosaics taken in November 1967 and March 1968. The maps were titled "Hydrographic Survey Maps of the Mississippi River, Mouth of the Ohio River, Mile 0 to Mile 300, U.S. Army Engineer District, St. Louis, Corps of Engineers, St. Louis Missouri.

TABLE I

SURFACE AREAS

Year	Surface Area sq mi	Island Area sq mi	Riverbed Area sq mi
1821	109	14	95
1888	163	35	128
1968	100	17	83

The 1888 areas represent conditions at the end of the "natural" river history. The 1968 figures include effects of river contraction efforts. As noted above, the contraction was accomplished by employing dike fields and bank revetment. In the period between 1888 and 1968 the river surface area has been reduced by approximately one-third, the island area by one-half, and the riverbed area by one-fourth.

We are not certain what events caused the increase in surface area, island area and riverbed area between 1821 and 1888. The 1821 maps are not exact (distance between St. Louis and Cairo is incorrect by a few miles) but the map errors are believed to be less than the changes in areas. It is possible that the large floods which occurred between 1844 and 1888 coupled with land use could have increased the surface and riverbed areas of the Middle Mississippi River.

RIVER WIDTHS

The river width is the distance from tree line to tree line irrespective of bank height taken normal to the general direction of flow in the river. In conjunction with the study of surface areas, river widths were measured at mile increments between Jefferson Barracks and Cairo. The river widths are given in the following table:

TABLE II

HISTORY OF RIVER WIDTHS

Year	Average Width ft
1821	3600
1888	5300
1968	3200

The 1888 average width was approximately two thousand feet greater than the 1821 and 1968 widths and the widths in 1821 and 1968 were nearly equal. The average widths have changed in the same manner as the surface areas discussed in the previous section. There has been no appreciable change in river length.

There is evidence that the river did widen from natural causes in the period between 1800 and 1849. At the St. Louis harbor the following history of bank-full widths has been obtained:

TABLE III

RIVER WIDTHS AT ST. LOUIS

Year	Width ft
1803	3100
1808	3200
1837	3700
1843	3900
1849	4200
1888	2100
1973	2100

Note: The widths for the period between 1803 and 1849 were obtained from Maher, 1963.

The river was definitely widening rapidly at St. Louis in the period from 1803 to 1849. The widening was deteriorating the St. Louis harbor and in 1838 the city and private corporations began work on a series of dikes from the Illinois shore to confine the river to a definite channel. The dikes reduced the river width by half, and since that time the bank-full width at St. Louis has remained 2100 feet.

It is possible that the large floods which occurred between 1844 and 1888, or a combination of large flood and floodplain development could have been the cause of the widening of the Middle Mississippi River reach. In that period there were four floods that equalled or exceeded 1,000,000 cfs.

CROSS-SECTIONAL AREAS

The Middle Mississippi River has been deepened for navigation by decreasing the width with rock and pile dikes. An example of the change of cross-sectional geometry is shown in Fig. 3. In 1837 the river section at St. Louis was 3,700 feet wide and had an average depth of 30 feet deep at bank-full stage. The dikes started in the 1830's and completed before 1888 decreased the width permanantly to 2,100 feet. In 1973 the average depth prior to the 1973 flood was about 45 feet at bank-full stage and the width-to-depth ratio has decreased from 123 to

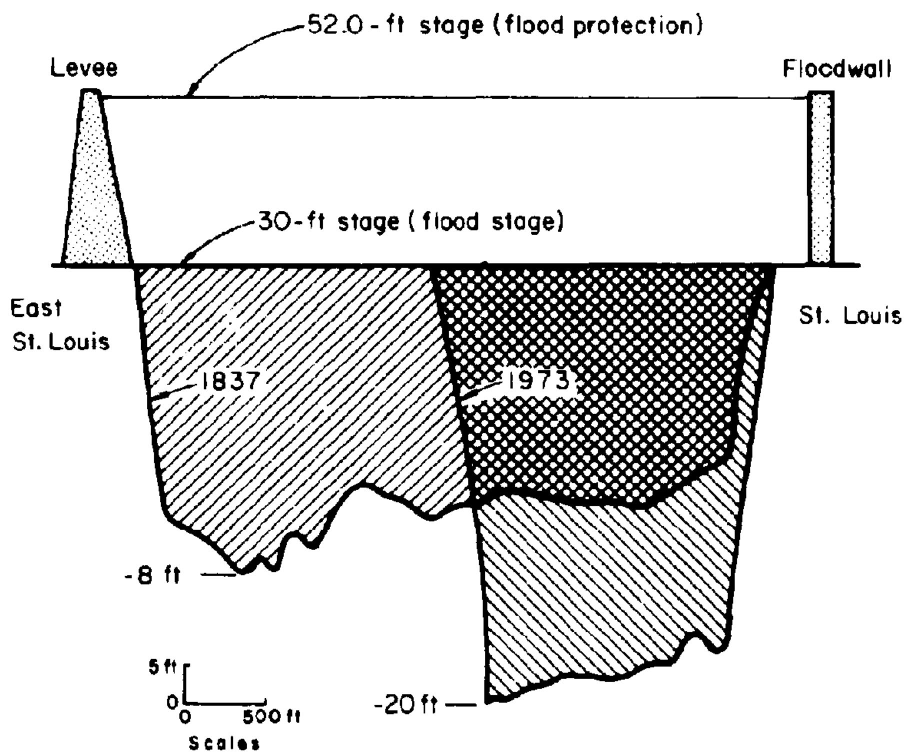


FIGURE 3 THE ST. LOUIS CROSS SECTION

47. The river has been maintained in the narrow channel at St. Louis by protecting the undiked bank in places where bank erosion would occur.

The cross-sectional area at bank-full stage is approximately 80,000 square feet in 1973 whereas the area was 120,000 square feet in 1837. The narrowing of the channel at St. Louis has reduced the bank-full channel area by about one-third. A similar decrease in the bank-full cross-sectional area has occurred throughout the Middle Mississippi river wherever the river channel has been contracted.

RIVERBED ELEVATIONS

In the previous section, we compared the cross sections of the river channel at St. Louis before and after river contraction (See Fig. 3). Narrowing the river section at St. Louis caused a general degradation of the bed. The bed was on the average 8 feet lower after contraction than before.

Riverbed degradation has occurred along the Middle Mississippi River wherever the river channel has been narrowed. The degradation is the natural consequence of reducing the width, increasing the flow per unit of width and increasing the transport capability of the water per unit width.

The riverbed elevations in a 14-mile reach of river are shown in Fig. 4. The average bed elevation, shown in Fig. 4, is the mean elevation of the riverbed in the low-water channel. The average bed elevation was determined as the average of between 10 and 20 riverbed elevations at a cross section. The riverbed elevation is not necessarily related to depth of flow but is the indicator of degradation or aggradation in the river.

The 1889 riverbed elevations describe the level of the riverbed in its natural state. The river in this 14-mile reach was about 4800 feet wide in 1889. By 1966 the river had been contracted to an average width of 1800 feet. The riverbed had lowered about 8 feet between 1889 and 1966. In July 1967, the Corps of Engineers selected this 14-mile reach as a test reach to develop design criteria on obtaining and maintaining a dependable 9-foot deep navigation channel. [Degenhardt, 1973]. Between 1967 and 1969, this test reach narrowed from 1800 feet to 1200 feet in width. In 1971, the riverbed was resurveyed. The 1971 bed profile is shown in Fig. 4. The contraction from 1800 feet to 1200 feet had resulted in a 3-foot lowering of the riverbed [Degenhardt, 1973]. In 1971 the low-water riverbed in the 14-mile reach between Mile 140 and Mile 154 was on the average 11 feet lower than in 1889.

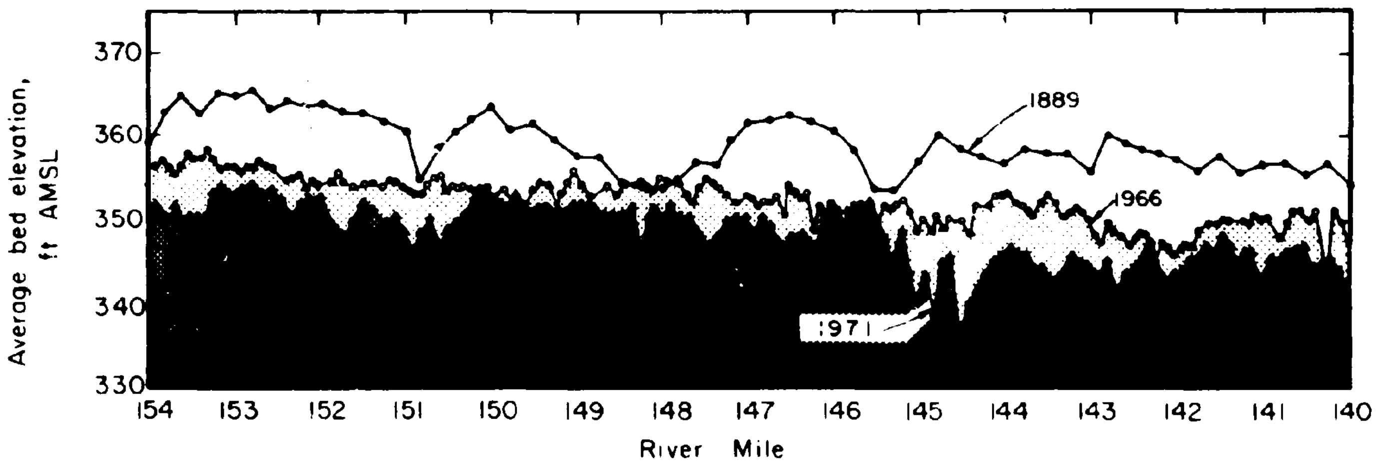


FIGURE 4 BED ELEVATIONS MILES 140 TO 154
[adapted from Degenhardt, 1973]

FLOWS

The water flows in the Middle Mississippi River have been measured at St. Louis intermittently from 1843 to 1861, and continuously since 1861. St. Louis is below the confluence of the Missouri and Upper Mississippi Rivers. The flood peak discharge of record at St. Louis was 1,300,000 cfs recorded in 1844. The Missouri River contributed 900,000 cfs, the flood record in the lower Missouri. The largest recorded flood in the Upper Mississippi was 565,000 cfs at Alton, Illinois which occurred in 1851 and again in 1858. The minimum discharge at St. Louis was 18,000 cfs which occurred in 1863.

The construction of levees along the floodplain was one of man's first influences to affect natural flows in the Middle Mississippi. The floodplain is a storage area for flood waters when the river rises above the bank-full stage. Also the floodplain provides some channel capacity to carry water on downstream. Hence, levees along the reach of river increase the flow discharges for discharges greater than bank-full stage. The increase in discharge results from the decrease in floodplain storage.

Because the floodplain was not protected by levees in 1844, the peak discharge of 1,300,000 cfs during the flood that year passed St. Louis at a 41.3-foot stage. Now due to the construction of contractive works and levee systems, the same discharge would pass St. Louis at approximately a 52.0-foot stage. While the peak discharge stage is now some 10 feet higher under developed conditions, as opposed to natural conditions, rural and urbanized areas suffer less flood damage under developed conditions due to the flood protection provided by levees than with no levees.

About 1907, levee construction in the Middle Mississippi began in earnest because the financing of levees was shifted from private land owners to government. Until this time, levees were not effective because of inadequate engineering capabilities and inadequate financial resources.

The next dominant factor to affect flows was the construction of storage dams on the Missouri River, but the first was not completed until 1940. The larger dams are Yellow Tail on the Yellowstone River and Fort Peck, Garrison, Oahe, Big Bend, Fort Randall and Gavins Point on the Missouri. The effects of these reservoirs on the flows depend on the method of operation. In general the reservoirs have the effect of decreasing the maximum flows and increasing the minimum flows.

Other factors which could influence the natural flows are changes in conditions that affect runoff from the drainage basin. These factors could be changes in the amount of precipitation and changes in the land uses. Also consumptive uses for irrigation and domestic use are other factors.

The net effect of upstream developments on the flows in the Middle Mississippi River at St. Louis are reflected in the St. Louis discharge records which are illustrated in Fig. 5. The effects are:

1. The average annual peak flood discharge has not changed much in 110 years. On the average the present-day peak floods are only slightly lower than previously.

2. Large flood flows are not occurring as frequently now as in the past. In the decade between 1850 and 1860 there were three flood peaks greater than 1,000,000 cfs. Flood flows in excess of 1,000,000 cfs have not occurred since 1903.

3. The mean annual discharge has not changed in 130 years.

4. The annual minimum flow has been increasing slightly during the 130 years of record.

In general, the conclusion is that storage reservoirs, levees, dikes, land use changes, and any climatic changes have, in aggregate, not significantly changed the average annual flow in the Middle Mississippi. In terms of flood control the affect is that very large and very small peak flood discharges were more common in the natural river than in the river today.

SEDIMENT DISCHARGE

It is the water flows delivered to the Middle Mississippi River by its tributaries and the Upper Mississippi River which sculpture the river form. The sediment flow is the supply of material which interacts with the erodable bed and bank material to determine the form of the river.

Nearly all of the sediment load delivered to the Middle Mississippi River comes from the Missouri River [Jordan, 1965]. That sediment carried in suspension is about 50 percent clay, 35 percent silt and 15 percent sand. The sediment moving along the bed of the river is fine sand.

It is anticipated that reservoirs on the main stem of the Missouri and reservoirs on heavy sediment contributors to the Missouri (the Platte River, for example) would have an effect on the Middle Mississippi River. We have not been able to identify any effects because the sediment records begin at St. Louis in 1948 after the closure of the first dams on the main stem of the Missouri River.

In the study of the 21 years of sediment records at St. Louis, there has been a trend to lesser amounts of sediment moving in the river since 1965 (See Fig. 6). Because the period of sediment record is short, not much significance can be attached to the apparent trend yet. The accumulated suspended sediment discharge values plotted in Fig. 6 are computed values of measured suspended sediment discharge adjusted to a common water discharge base of 100,000,000 acre-feet

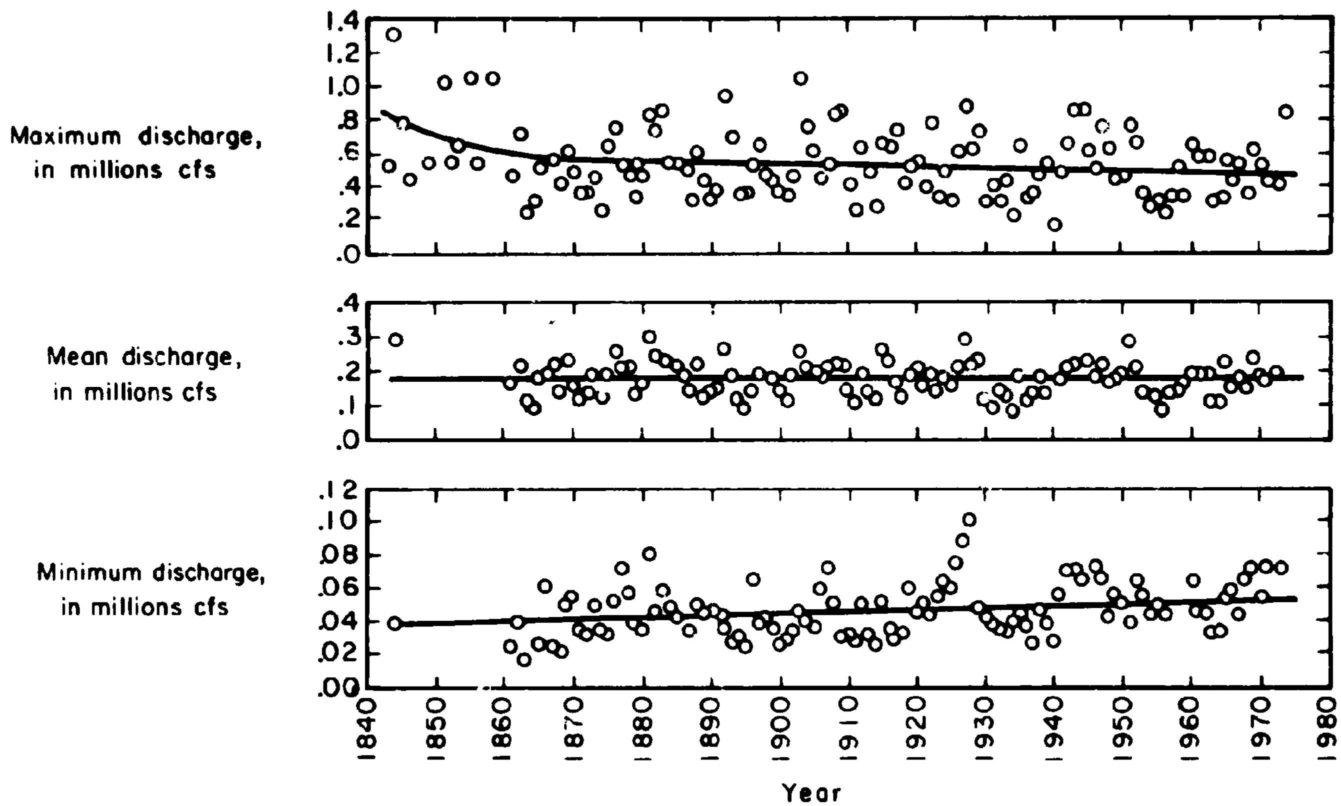


FIGURE 5 DISCHARGES AT ST. LOUIS

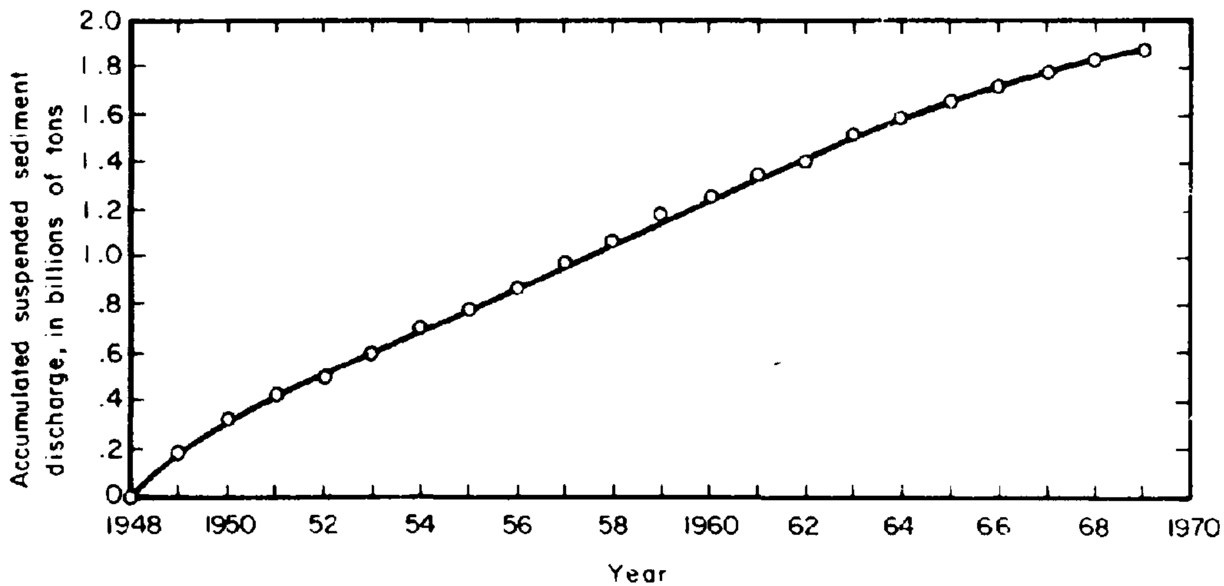


FIGURE 6 TRENDS IN SEDIMENT DISCHARGE AT ST. LOUIS

in one year. The relation between water and sediment discharge was taken from Jordan's report [1965]. The trend may be due to upstream development.

If the delivery of sediment to the Middle Mississippi River is being decreased by upstream storage reservoirs or other development, it is anticipated that the river channel will deepen slightly because of degradation induced by upstream storage of sediment.

STAGES

The St. Louis river stage records begin in 1843, are intermittent for the period up to 1861, and are continuous on a daily basis thereafter. The annual maximum and minimum stages on the Market Street gage are shown in Fig. 7. The zero of the Market Street gage is 379.94 feet above mean sea level.

The annual maximum stage at St. Louis has been increasing only slightly throughout the 130 years of records. The variations in annual maximum stages are greater now than in the past. The highest recorded stage in St. Louis was 43.3 feet in 1973.

The trend of the annual minimum stages is downward during the period of record (Fig. 7). The minimum stages are now on the average 6 feet lower than in the 1860's and the 1870's. The lowest minimum stage at St. Louis was -6.2 feet on January 16, 1940.

The study of the daily stage versus duration curves reveal that, on the average, daily stages are lower now than a century ago. In the period 1861-1900 the stage equaled or exceeded 50 percent of the time was 11 feet whereas in the later period it was 2.5 feet lower. There have been more very low and very high stages in the last 70 years than in the first 40 years of record.

STAGE VERSUS DISCHARGE AT ST. LOUIS

The effects of 100 years of development in the Middle Mississippi River on river stage, were illustrated with the occurrence of the 1973 flood. The 1973 peak flood discharge at St. Louis was 852,000 cfs, which resulted in a maximum record high-water stage of 43.3 feet. The 1844 record discharge of 1,300,000 cfs would now pass St. Louis with an estimated stage of 52.0 feet instead of the 41.3 feet of 1844.

The largest flood discharges at St. Louis are listed in Table IV. The 1973 flood ranks No. 10. The record high stages are listed in Table V. The 1973 flood stage ranks No. 1.

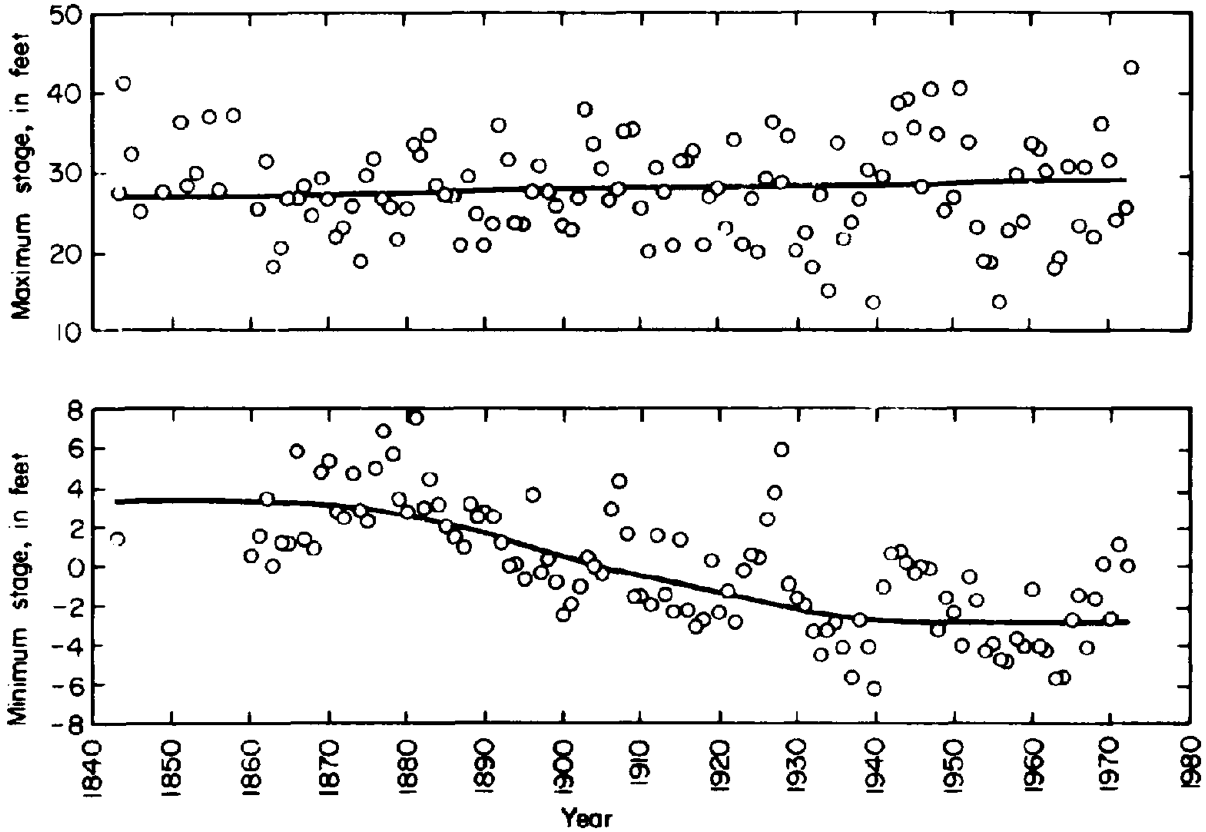


FIGURE 7 STAGES AT ST. LOUIS

TABLE IV

THE TOP-TEN FLOOD DISCHARGES AT ST. LOUIS

Rank	Peak Discharge cfs	Year
1	1,300,000	1844
2	1,054,000	1858
3	1,050,000	1855
4	1,040,000	1903
5	1,022,000	1851
6	926,000	1892
7	889,000	1927
8	863,000	1883
9	861,000	1909
10	855,000	1973

The period of record is 1843 to 1973

TABLE V

THE TOP-TEN FLOOD STAGES
AT ST. LOUIS

Rank	Maximum Stage ft	Year
1	43.3	1973
2	41.3	1844
3	40.2	1947
4	40.2	1951
5	39.0	1944
6	38.9	1943
7	38.0	1903
8	37.2	1858
9	37.1	1855
10	36.6	1851

The period of record is 1843 to 1973

The Nos. 6,7,8 and 10 ranked flood discharges had stages which do not make the top-ten list of flood stages. Conversely, the floods with stages ranked Nos. 3,4,5, and 6 are not found in the top-ten list of flood discharges.

We can see clearly what is happening to the flood stage versus discharge relation at St. Louis by studying, in historical sequence, all the floods with the same magnitude of discharge as the 1973 flood. Those floods are listed in Table VI. The list shows the steady increase in maximum stage for these floods in the last century. When the 1973 magnitude flood discharge occurred in the "natural" river, the stage was nearly 10 feet lower than in the "developed" river.

The picture of changing stages for all different discharges at St. Louis is given in Fig. 8. The change in stage is the present-day stage less the stage for the same discharge in the 19th century. The change in stage versus discharge curve was produced by analyzing all the stages for a given discharge for the period of record. For example, in Table VI the present-day stage for 850,000 cfs is approximately 9.5 feet higher than the stage 100 years ago. Thus, in Fig. 8, at a discharge of .85 million cfs, the change in stage is indicated as +9.5 feet.

The estimate of the change in stage at 40,000 cfs was taken from Maher [1963]. The increase in stage value at 1,300,000 cfs is the Corps of Engineers' estimate of the stage at St. Louis for the St. Louis District urban design flood (200-year flood).

For all flows above 300,000 cfs the stages are now higher. For flows below 300,000 cfs present-day stages at St. Louis are less than in the period before contraction to improve navigation.

The reason for the changes in water stage at St. Louis in the last century is due to the rock and/or pile dikes and the levees. Construction of rock and pile dikes cause deposition in the dike field, trees and willows grow on the deposit and stabilize the deposit. The tree and willow growth encourages additional deposition whenever the area is flooded. In most cases the ultimate effect of the dike field is to cause the river to develop a new bank line at the extremity of the dike field resulting in reduced channel width and a lowering of the riverbed level. The levees have isolated the major portion of the floodplain from the river channel so that all flood waters are now confined to the river channel and that portion of the floodplain between the channel and the levees.

Because the bed is lower in the contracted river, the stages are lower than in the natural river most of the time. For a flow of 54,000 cfs, the stage was approximately 11 feet lower in 1946 than in 1837. (see Fig. 9a).

The stage for which the 1837 and 1946 cross-sectional areas were equal was 19 feet. The discharge was 290,000 cfs for a 19-foot stage in 1946 and the area was 64,000 square feet (Fig. 9b).

TABLE VI

STAGES FOR SIMILAR DISCHARGES AT ST. LOUIS

Year	Maximum Stage ft	Discharge cfs
1881	33.6	822,000
1883	34.8	863,000
1908	35.0	850,000
1909	35.2	861,000
1927	36.1	889,000
1943	38.9	840,000
1944	39.0	844,000
1973	43.3	855,000

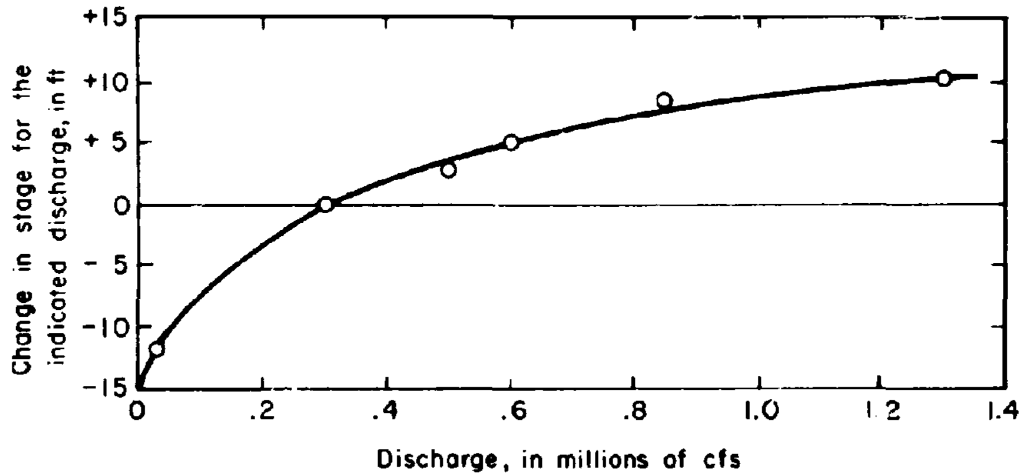


FIGURE 8 CHANGING STAGES AT ST. LOUIS

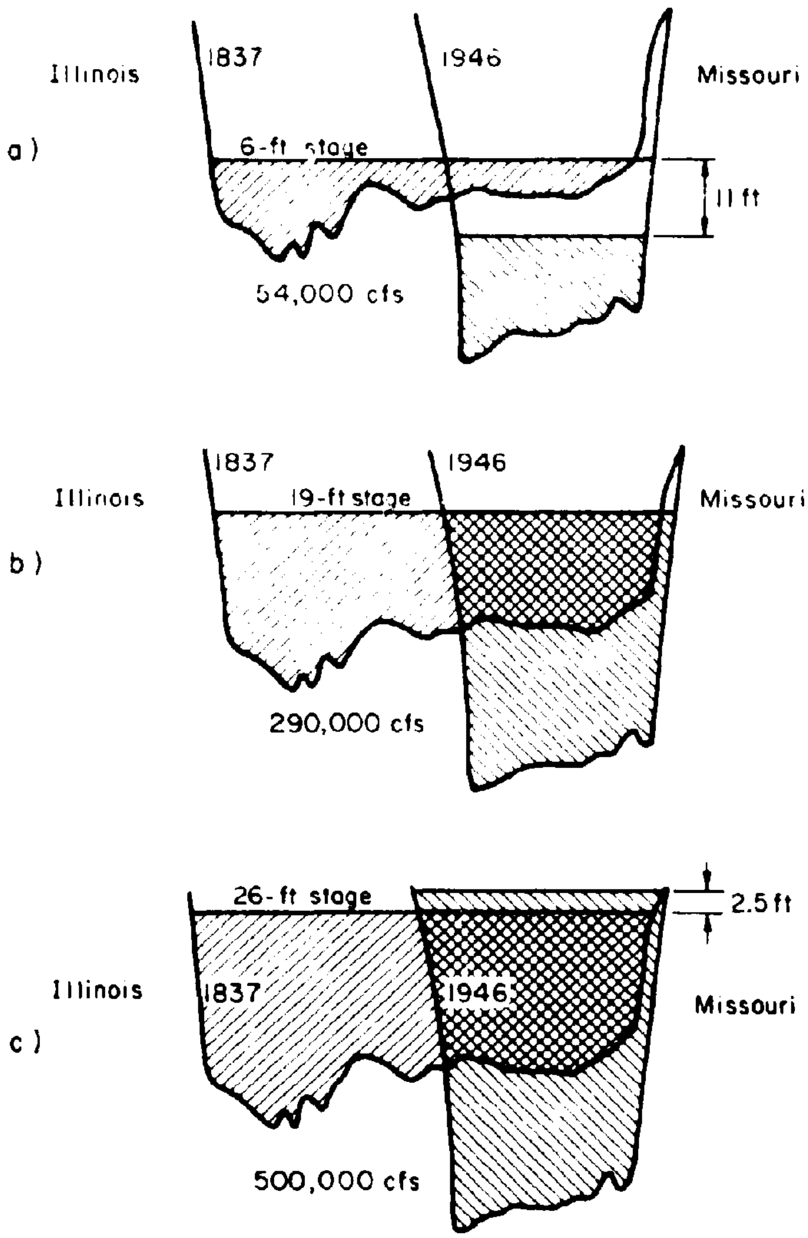
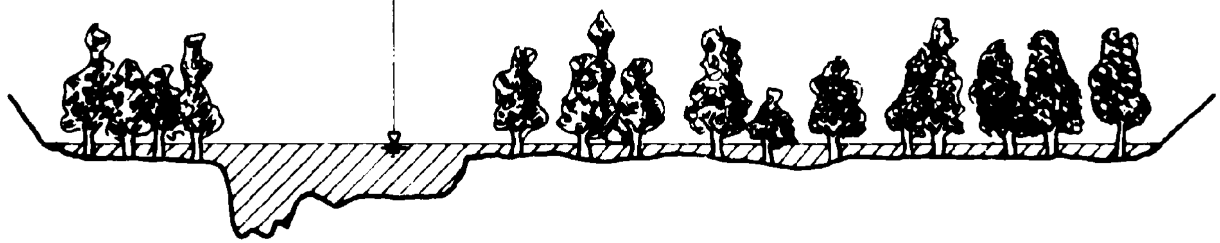
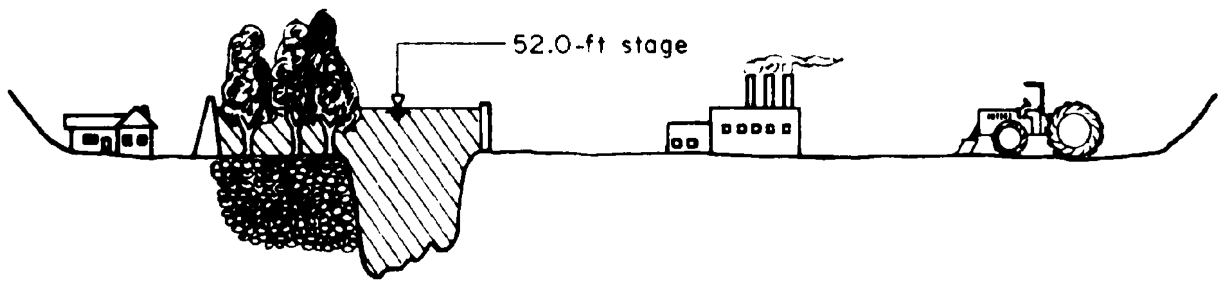


FIGURE 9 FLOW AREAS AT ST. LOUIS



d. The 1844 River Cross Section



e. The 1973 River Cross Section

FIGURE 9 THE CROSS SECTION FOR 1,300,000 CFS

For discharges greater than approximately 300,000 cfs but less than 500,000 cfs, the increase in present-day river stage above the former natural river stage is due solely to the dikes. Because the channel below bank-full stage is much narrower in the contracted river, the stage for a flow of 500,000 cfs is greater than in the natural river. For a flow of 500,000 cfs (the average annual peak flood) the cross-sectional areas occupied by the flow are shown in Fig. 9c. At 500,000 cfs, the 1946 stage was 2.5 ft higher than the 1837 stage.

Once the river flows spill overbank, the levees as well as the dikes affect the high-water stages in the channel. For discharges slightly greater than bank-full, the affect of the levees on the stage is small. The former floodplain (now protected by the levees) was not efficient at carrying shallow flows. For larger floods, the floodplain carried more water than at lesser floods. The effect of the levees on the stages of these larger floods is more pronounced than at lesser floods.

There is some flood discharge greater than bank-full for which the increase in stage caused by levees is equal to the increase in stage caused by dikes. For floods greater than this flood, the effect of the levees on the peak stage is greater than the effect of the dikes on the peak stage.

In Fig. 9d, we have perceived what a cross section of the Middle Mississippi River at St. Louis could have looked like during the 1844 flood of 1,300,000 cfs. The corresponding stage at St. Louis was 41.3 feet. Since levees and dikes have been constructed in the Middle Mississippi River, there has been no flood of the magnitude of 1,300,000 cfs. According to the present-day assessment of the river behavior, the 1,300,000 cfs flood would pass St. Louis now with a high-water stage of 52.0 feet. The present-day cross section of the Middle Mississippi River at St. Louis would appear as shown in Fig. 9e for a flood of 1,300,000 cfs.

The increase in river stage for any particular flood is the result of the combined effects of levees on the floodplain, dikes in the river channel and alterations of the floodplain between the levees and the river channel due to land use changes.

The question of the relative effects of dikes and levees on high-water stages in the Middle Mississippi River can only be answered by careful engineering study of the records available for this river. A separate study of this issue is warranted. We, the writers, have made the preliminary assessments given above as a starting point for the discussion of the response of the Middle Mississippi River to past developments. In terms of future developments, the assessment of past response is not critical. It is the correct assessment of future responses to programs being carried out at the present time that is important. The second portion of this report is to qualitatively address the problem of future responses in the Middle Mississippi River.

SUMMARY

The history of developments and modifications in the Middle Mississippi River in the last century have changed the form and behavior of the river. The objectives of develpments have been to provide flood protection to the people and property on the floodplain and to provide a suitable channel for navigation.

We believe that the Middle Mississippi River was mostly unaffected by upstream developments in the 19th century. Within the 20th century the Middle Mississippi River has been contracted to provide the navigation channel and it has been leveed to protect the people and property from floods.

In response to man-induced modifications, the changes in the form and behavior of the Middle Mississippi River have been as follows:

1. The position of the river in the valley is basically unchanged in the last 200 years and, in the absence of earthquakes or great floods, should remain so.

2. The surface area of the river has been greatly reduced since the 1880's, but may not be reduced much from the average value it would attain if left unrestricted over a long period of time and without the adverse effects of very large floods and with the aid of bank-line vegetation.

3. The river flows have changed very little. The very large peak flows do not occur as frequently now as in the past. The annual minimum flow is larger now and the mean annual flow is unchanged.

4. The annual maximum flood stage at St. Louis has been increasing slightly in the last 100 years; the annual minimum stage has decreased significantly.

5. Except for stages greater than 20 feet, daily stages at St. Louis are lower now than in the past.

6. At all discharges the depth of water in the river is greater now than before modification.

7. The change in the river cross section has reduced the flow carrying capacity of the river channel for flows greater than bank-full. The levees have isolated the main channel from its floodplain and the dikes have constricted the main channel. Stages for flood discharges are higher now than in the past.

8. From the flood protection point of view, present-day floods produce a flood stage greater than those for comparable discharges in the 1800's.

Although flood stages are now higher than those under natural conditions, levees prevent flood damage when the Middle Mississippi River exceeds bank-full stage. Under natural conditions flood damage occurred whenever the river exceeded bank-full stage.

By encouraging deposition and tree and willow growth, the dikes have helped produce a stable low-water channel which is a part in one of the worlds' largest inland water transportation systems. The economic benefits of this system to the American people are undoubtedly very great.

SIDE CHANNELS

INTRODUCTION

The directive from Congress to the Corps of Engineers is to develop the 9-foot deep low-water navigation channel from Cairo, Illinois to St. Louis, Missouri. In order to achieve this depth, the unobstructed river channel will be narrowed to a width of approximately 1500 feet by projecting rock dikes from one or both river banks into the channel. Some water areas will exist within the dike fields and the actual water surface width will be greater than 1500 feet but different for each reach of the river. When necessary the opposite bank line will be protected with revetment to control migration of that bank line. In planning these contraction works, the Corps of Engineers is endeavoring to optimize the project to meet the goals of environment, conservation, and flood control interests as well as those of navigation.

The planned contractions on the Middle Mississippi River will produce bank-full stage at less discharge. Also the planned contractions will lower the bed elevation of the channel and produce lower water stages at low discharges. In the past, river contraction works have created new islands, side channels and floodplain lands.

The side channels of the Middle Mississippi are of ecological interest because they provide a favorable habitat for aquatic life in the river. This issue is being evaluated separately by qualified experts. Moreover, the islands between the side channels and the main channel are not readily accessible to man and therefore may provide a sanctuary for wildlife.

In the Middle Mississippi,some side channels were natural in origin. Picayune Chute shown in Fig. 10 is such a channel. Many of the more recent side channels in the Middle Mississippi River are the result of dike field construction by the Corps of Engineers to improve the navigation channel (Degenhardt, 1973).

The interest in side channels leads to the question of how side channels form, how side channels change with time, and what is the effect of navigation improvement works on side channels. It is especially important to understand why some natural side channels have existed for more than 100 years whereas others fill and are obliterated within a decade. Herein, the formation and destruction of natural side channels in the natural river are discussed. Examples of the formation and destruction of natural side channels are taken from field studies and from laboratory model studies.

We have made a detailed laboratory model study of the evolutionary development of side channels in dike fields. Generally speaking, side channels in the dike fields fill rapidly with sediment because dike fields are usually located in areas of natural deposition. In the model studies the methods of prolonging the life of man-made side channels have been studied.

FIGURE 10 PICAYUNE CHUTE IN 1972.

DEFINITIONS

What is a side channel? Where a river section is divided into two or more channels by islands the larger channel is called the main channel and the smaller channels are the side channels. The islands are vegetated areas and are relatively permanent in contrast to midchannel sandbars. The word bar is restricted to mean a nonvegetated sandbar.

In the Middle Mississippi River, side channels which carry appreciable river flows at least during the flood season are called chutes. The bed of a chute is composed of about the same materials as the main channel bed. A chute cutoff is a chute across the bend or across a meander loop.

In the St. Louis District, flood stage refers to a specified stage at which some damages may be experienced on the floodplain inside the levees. At St. Louis flood stage exceeds 30 feet on the Market Street gage. In this report, stages above flood stage are called high-water stages.

Side channels which do not carry appreciable river flows at high-water stage are called backwater channels. They are usually smaller than chute channels and provide very little storage for flood water. Consequently the bed of a backwater channel is composed of fine materials that have settled out of the slack water.

GENERAL PRINCIPLES

Much is known about the mechanisms of flow in rivers. This knowledge of river behavior is essential to understanding the complex interaction between water and sediment, between main channel and side channel, and between man-made structures and river flows. Below, a list of some general river mechanics principles is made to facilitate understanding what is going on in the river channel. The general principles are valid, in the most part, for laboratory models and greatly aid in the interpretation of laboratory model tests.

The first principle concerns momentum. Momentum dictates that it is easier to turn a corner in your car at a low speed than at a high speed. In river mechanics, momentum compels fast-moving water to continue in a straight path but allows slow-moving water to select more tortuous paths of travel.

The second principle is that, given the choice of two channels, most of the water will flow in the channel with fewer impediments to flow.

The third principle is that the fast-moving water is found at or near the surface of the river and the slow-moving water is at the bed.

The fourth principle is a statement of the fact that most of the coarse sediments carried by most rivers are moved along or near the bed of the river during periods of flood flow.

The principles set forth above have been proven in both laboratory and field situations. Sir Claude Inglis [1949] used these principles successfully to separate water and sediment at canal offtakes from rivers. At times he was too successful and was requested to alter his designs to allow a little sediment to pass into the canals. Franco [1972] has grouped the four principles into one statement:

> "When conditions are such that a lateral differential in water-surface elevation exists or is produced by changes there will be a tendency for at least some of the total flow to move towards the lower elevation; the slower-moving sediment-laden bottom currents can make the change in direction easier than the faster-moving surface currents and account for the tendency for the greater concentration of the sediment moving toward the lower elevation."

The lateral differential in water surface elevation is somewhat equivalent to an offtake canal. The water has a choice between going on downstream or changing direction and flowing laterally. Franco's statement that slow-moving sediment-laden bottom currents can make the change in direction easier under the right alignment conditions encompasses the first, third and fourth principles listed above.

With reference to the general principles, it is easy to understand the lateral separation of water and sediment that occurs at river bends. In a bend there is a concentration of the fast-moving water on the outside of the bend and a concentration of the slow-moving water on the inside of the bend. Helical flow moves the material toward the inside bank. The outside current carries more sediment than the inside current which has a lower carrying capacity. The result is that sediments are deposited on the inside of the bend and form a point bar.

If one wants to divert clear water from a river channel into a side channel, there is only one position to locate the channel offtake. That location is at the outside of the downstream end of the bend. That location will be successful only if the offtake channel is aligned closely with the surface velocity flow in the main channel. At all other locations and alignments, the offtake channel gets more than its fair share of the sediment.

CSU LABORATORY STUDIES

As a part of the study of the effects of channel contractions on the geomorphology of the Middle Mississippi River, Colorado State University constructed a physical model representing straight reaches and bend reaches of a river channel. The model was constructed in the River Research Flume in the Hydraulics Laboratory at the Engineering Research Center. The model was not a sealed hydraulic model but rather a geomorphic model which shows sedimentation and erosion processes.

The River Research Flume is a 20-foot wide by 100-foot long sandbed flume. A 6-foot wide channel was formed in the sand. The sandbanks of the channel were stabilized with mortar. In the CSU model, we did not have a floodplain. The riverbanks in the model were to represent the riverbanks and levees or bluff lines in the Middle Mississippi River. The bed material was 0.8 mm sand. Dike fields were built into different reaches of the river channel. The dikes were constructed with riverbed sand covered with a stabilizing mix of sand and cement. The dikes had a 1.5:1 slope on the upstream face and a 2:1 slope on the downstream face. The dike lengths were varied from 10 inches to 28 inches depending on the location of the dike. Dike crest elevations were established so that the dike was submerged at large flows but exposed at low flows.

The flow rate in the model was varied between 0.25 and 1.5 cfs in a manner so as to reproduce the form of the yearly flow duration curve in the Middle Mississippi River. Although there was movement of sediment in the model crossings at low flows, sediment transport in the model was significant only at the larger flow rates. That is, except for a few bed adjustments, the low-flow discharge followed the channel established at higher flow rates.

In the model there was a small amount of clay mixed in with the sand. This clay was moved as suspended load and was desposited in backwater areas where the currents were very small. These clay deposits were very thin and did not change the geometry of the backwater areas appreciably.

The CSU sandbed model was operated in such a manner as to produce bars, scour holes and other riverbed forms which occur in the Middle Mississippi River. We have assumed that the water and sediment transport processes which produce these same riverbed forms are the same in the model and in the Middle Mississippi River. Herein examples are taken from the many model study tests to illustrate the interaction between water and sediment, and between main channel and side channels.

NATURAL SIDE CHANNELS

INTRODUCTION

In the Middle Mississippi River, there are natural side channels that have been in existence for at least 160 years. The side channel at Cape Bend immediately below Cape Girardeau is one; another is Picayune Chute which is approximately seven miles upstream of Cape Girardeau (see Fig. 1). Others exist but only these two were studied in detail. We have studied the 160-year history of these two side channels. The bank-line configuration of Cape Bend and Picayune Chute for the years 1810, 1880, 1907, 1927, 1937, 1946, and 1969 are given in Appendix B. The 1810 map was prepared by Stevens from the original township survey plots. The other maps are copies of maps that were prepared by the Mississippi River Commission or U.S. Army Engineer District, St. Louis. The changes in the period between 1810 and 1927 in the Cape Bend and Picayune side channels are changes brought about by naturally occurring events. Thereafter many river control structures were built into these reaches.

In the natural river, side channels and islands are formed because of a complex series of events. In this chapter the ways in which a natural channel becomes divided are explained. Two situations are considered. The first is the division of a straight channel into two channels and the second is the development of a side channel at a bend.

STRAIGHT CHANNEL

The division of a straight reach of river channel into two channels is accomplished with the formation of an island within the channel. The island is a vegetated middle bar built up of materials deposited when the flow could no longer carry the sediments. The decrease in sediment transport could be caused by a local obstruction or by a change in slope. Straight reaches of river with many islands and channels are called braided reaches.

Braided river reaches are usually found below tributaries which contribute large amounts of sediment or below narrow contractions in a straight reach. Commonly, rivers are braided on alluvial fans. Rivers on steep slopes carrying large amounts of sediment are characteristically straight and braided.

A Case History

In the 1800's, the Middle Mississippi River was braided throughout a large portion of its length. The 1880 bank-line maps in Appendix A show a great number of islands. The best documented and unusual case of island and side channel evolution is that reported by Shull [1922, 1944] in the Lower Mississippi River near Belmont, Missouri.

In this case an island formed in an existing chute channel when a large barge became stranded in the chute during the recession of the 1913 flood (Shull, 1922). The chute was a good depositional area. Within six years the island grew to a length of three-quarters mile, a width of one-eighth mile and an area of approximately 60 acres. The island was composed of light-colored sandy silt and was covered with a "beautiful" growth of young cottonwood trees from 4 to 8 inches in diameter and 30 to 40 feet tall. Each succeeding flood that inundated this new island added more material to its dimensions. The 1920 flood deposited 16 to 18 inches of sandy silt over the entire area.

In 1919 the chute between the island and the Missouri bank was beginning to fill. A younger belt of cottonwoods was encroaching on the chute from the island side and on the Missouri bank a growth of breast-high willows and belt-high cottonwoods lined the chute.

Shull predicted that before many years the island may be joined to the Missouri mainland. In 1933 he visited the region again and reported that the island had indeed become a part of the Missouri mainland:

> "The old chute of the river is now occupied by a thick growth of willows..., among which mud deposits have developed to such a depth that the old channel is almost level with the flood plain along the bank of the Missouri shore. The filling of the channel and the deposition of mud all over the island has proceeded with every flood whose crest has been higher than the island..."
>
> "The character of the soil has changed markedly all over the area. Formerly a cottonwood island with sandy deposits, it is now completely covered with a soft mud. This mud soil seems especially favorable to willows, and the extensions of the island vegetation to the north and west [into the Missouri-side chute] since 1919 consists almost exclusively of black willows" [Shull, 1944].

The cottonwoods, which were 4 to 8 inches in diameter and 30 to 40 feet tall in 1919, were about 18 inches in diameter and 100 feet tall in 1933. It was estimated that 3 feet of mud had been deposited on the surface of the island in 9 years. That is a rate of approximately 4 inches per year.

In the early history of the Middle Mississippi River, the depositional environment necessary to produce a divided channel was often created by floating trees snagging on sand bars during the flood recession. Bed currents would sweep around the snag and deposit sediments in its wake. The succeeding floods were not able to remove the deposition and vegetation took hold, forming an island and a side channel.

In this example of the formation of an island and destruction of a side channel in a straight reach of undeveloped river the sequence of events was:

1. The existence of a depositional environment within the existing channel;

2. The arrival of a local disturbance, the barge, which triggered the rapid deposition of a sand bar;

3. The establishment of vegetation, cottonwoods, on the bar. At this point in time the sand bar became an island;

4. The encroachment of the island and mainland banks into the side channel;

5. The deposition of mud over the whole area when flows became essentially slack water; that is, the side channel became a backwater channel;

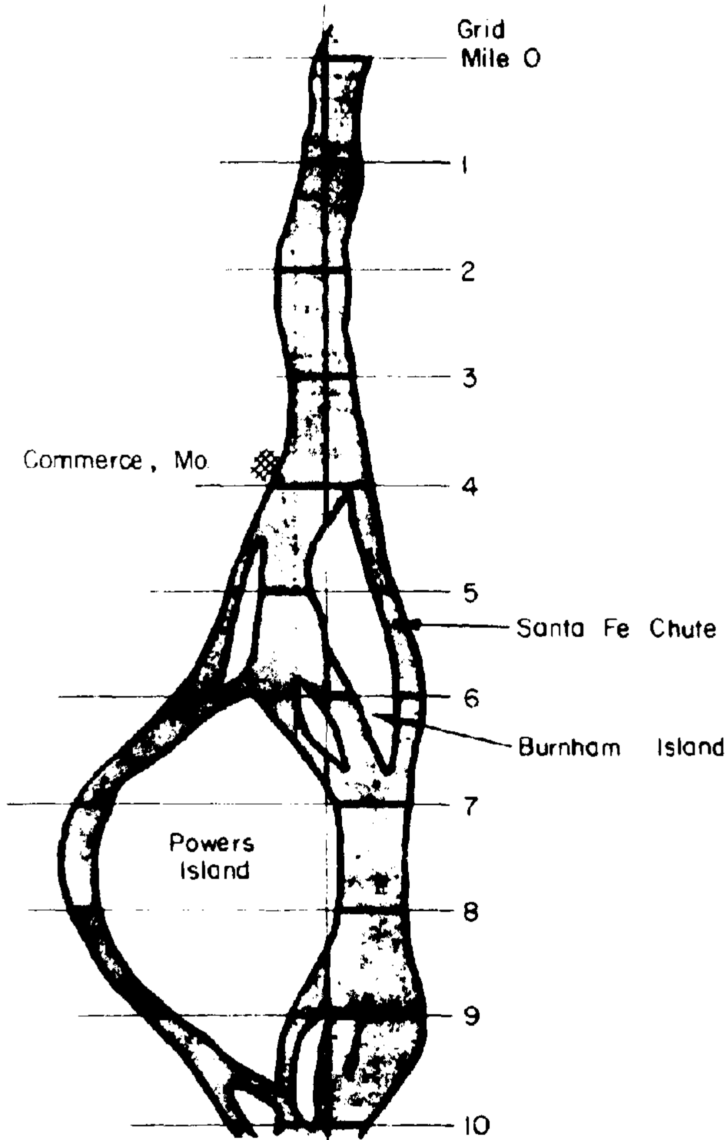
6. The ultimate merger of the island with the mainland floodplain, thus ending the existence of the backwater channel.

Another Example

Where bedrock constricts a channel and prevents a section of river from attaining its average alluvial width, islands will usually form immediately downstream. The islands are formed from material which was scoured in the contracted section during floods. Scour and subsequent fill in a contracted reach during a flood passage has been illustrated by Leopold, Wolman and Miller [1964, p. 229]. The sediments which are eroded from the bed of the contracted reach during the rising portion of the flood are deposited in the wider reach immediately downstream. During falling stages, the scour areas in the narrower section are filled again with sediments and erosion occurs in the downstream section. The erosion in the downstream section reestablishes the main channel depth and those side channels which are usually chutes.

In the Middle Mississippi, the Thebes Gap reach is a naturally contracted reach. Thebes Gap is the reach of river between Grid Mile 0 and Grid Mile 3 (in Fig. 11). The width is controlled by rock outcroppings, but the bed is alluvial except for local bedrock outcrops. In 1884, the reach of river below Thebes Gap was braided. The 1884 banklines and islands are shown in Fig. 11. The 1884 hydrographic survey may have been the last survey of this river reach in its natural state. The largest island was called Powers Island, which was nearly six square miles in surface area. The second largest island was Burnham Island, which was one square mile in area. All side channels in this reach were chutes in 1884.

At present (1973), Powers Island is joined to the Missouri mainland, but Burnham Island still exists. Santa Fe chute between Burnham Island and the Illinois mainland is now considered a backwater channel. All other chutes in the Powers Island area have been closed by river contraction work. The Santa Fe side channel will be discussed in more detail in a later section.



1884

FIGURE 11 THE THEBES GAP REACH

A Laboratory Study

Leopold, Wolman and Miller [1964, p. 284] described the formation of islands and chutes in a laboratory model as follows:

> "In flume experiments conducted in a channel molded in moist but uncemented sand, the introduction into the flowing water of poorly sorted debris at the upper end produced, with time, forms similar in many respects to those observed in the field. After 3 hours a small deposit of grains somewhat coarser than the average introduced load had accumulated on the bed in the center of the channel. This represented a lag deposit of the coarser fraction which could not be carried [any farther] by the flow..."
>
> "The growth surfaceward of a central bar tends to concentrate flow in the flanking channels, which then scours their bed or erodes their banks (or both)... As the cross section is enlarged, the water surface elevation is lowered, and the bar, formerly just covered with water, emerges as an island. In a natural stream the emergent bar may be stabilized by vegetation which prevents the island from being easily eroded and in addition tends to trap fine sediment during high flow. Thus the ground tends to become veneered with silt."

Conclusions

The features of side channel formation in both the Powers Island reach and in the laboratory model discussed above were the same as those described by Shull. A straight reach of channel will divide if we have the right depositional environment and a trigger mechanism to start the deposition. The development of vegetation on the deposition enhances the deposition process and makes the bar more permanent. In Shull's case the side channels filled naturally. In the Powers Island reach most of the side channels were closed with the help of engineering works.

MEANDERING CHANNEL

In a meandering river, the division of the main channel into two or more channels can occur at bends, meander loops and straight reaches. The formation of side channels at a bendway may be due to bank-line migrations at the side channels at the bendway, but side channels also occur in the absence of bank-line migrations. The water hydrograph plays an important role in the formation of side channels in natural rivers, but side channels form in the laboratory model bendways when the discharge is held constant. In some bends, the side channel captures the main channel flow leaving the main channel with only a side channel status. In other cases, the side channel at a bendway fills rapidly. The key to understanding the complex situations that can occur at bends lies in the understanding of why rivers meander. We, the authors, do

not have a completely satisfactory understanding of why rivers meander and therefore are left with the task of studying case histories of migrations of meandering channels.

Point Bar Cutoffs

The formation of a channel across the inside of a bar by erosion during large floods is a common occurrence. An example is the Arkansas River in Colorado. The 1973 flood incised a channel across most of the point bars in the lower Colorado reach of the Arkansas River. Immediately prior to the flood there were no such channels.

Point bar cutoffs occur during the high flows because at large flow velocities, the momentum of the flow dictates that the flow travel a less tortuous path. That is, during floods, the flow straightens out in the river channel. Some of the flood water short circuits the low water thalweg route around the outside of the bend and develops a channel across the point bar adjacent to the convex bank. Once the flow waters recede, we are left with the main channel on the concave side, a middle bar, and channel on the convex side of the bend. If the middle bar becomes vegetated a chute channel is formed.

At lesser flows the channel on the convex side of the bend fills with sediment carried in by slow moving sediment-laden bed currents flowing around the inside of the bend.

Meander Loop Cutoffs

The meander loop chute cutoff is formed by the same process as the point bar cutoff but on a larger scale. During floods, the momentum of the surface water carries that water across the neck of the meander loop. If the short circuiting water can scour out a channel, a chute cutoff of the meander loop is formed. This chute channel develops into the main channel and meander loop channel becomes an oxbow lake.

Potential for a meander loop chute cutoff is large where the length of the meander loop channel is many times the distance across the neck. The chute cutoff would be accomplished most likely by a large flood.

When a cutoff is the result of the migration of one bend into another, no chute is formed; the cross connection is a gooseneck cutoff or merely a cutoff. The meander loop abandoned by the cutoff becomes the oxbow lake.

Lateral Bank-line Migration

If the bank-line migration is normal to the river valley, side channels form on the inside of bends. The process of formation is different than the point bar cutoff. The point bar cutoff is formed by erosion whereas in the lateral migration case, the side channel is usually a depositional feature on the inside of the bank. The size of the side channel is enhanced at times by flood waters.

Ruhe, Fenton and Ledesma [1972] have studied the history of the mobile Otoe Bend in the Missouri River near Nebraska City, Nebraska. From soil surveys and surface topography and hydrographic surveys, the 19th century bend migrations have been determined. In the period between 1852 and 1879, Otoe Bend was migrating laterally eastward. In this period the depositions on the convex part of the bend are shown as the shaded area in the 1879 map in Fig. 12. A system of side channels separated the new islands in 1879.

In the period between 1879 and 1890 the migration was initially eastward, but later the river began to move westward. As the eastern migration continued, more accretions were added to the inside of the bend. These accretions and islands which formed between 1879 and 1890 are shown on the 1890 map in Fig. 12. On the western side, previously formed side channels were filled and new side channels farther east were established. Deposition resulting from the return migration westward are not so easily identified. In 1890 the bend was braided with three well defined chute channels and one backwater channel.

Ruhe, Fenton and Ledesma [1972] made these generalizations about side channels:

> "They form in bed and bank accretions in a braided stream channel. They commonly form at and along the contact between bank accretions and the bank. They commonly form in the bank accretion as the main channel shifts away from the bank. They form concurrently along opposing convex and concave banks. They form in accretion deposits near and distant from the main channel. They never are the main channel. They become landlocked by stabilization of bank accretion and shift of the main channel away from the bank accretion. Landlocking of chutes is a normal, gradual process..."

If bend migration is halted by bank revetment for example, the divided channel configuration will be stable if the upstream conditions are favorable. If migration continues the side channel can deteriorate in both size and flow-carrying capacity, and become a backwater channel. Other side channels and islands form as the bend migrates outward. Sometimes the side channel enlarges, but in that case the flow in the main channel is decreased and the bend migration is arrested.

Downstream Migration

In our laboratory experiments on migrating river channel forms, chute cutoffs on point bars occurred as a result of the downstream migration of the thalweg on the point bar. In these model tests a constant water flow was discharged through an artificial bend into a deep and narrow preformed channel with sandbanks and bed. A meandering thalweg pattern developed and migrated downstream in a uniform manner. The essential features of the model were an aggrading bed and a widening cross section. Most of the sediment in motion was derived from caving banks. The sediment eroded from the outside of the bend and was deposited on the point bar immediately downstream. The plan-view appearance of the laboratory channel before cutoffs formed is shown in Fig. 13a.

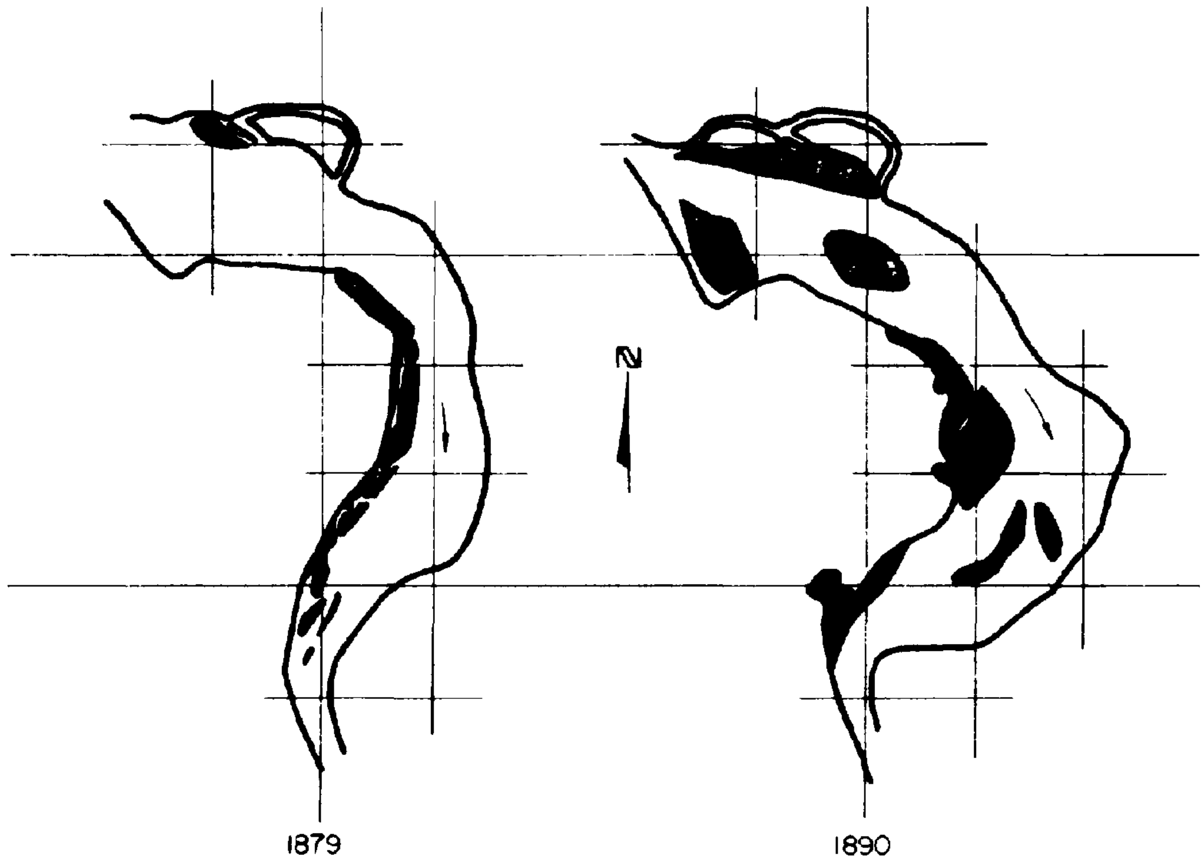
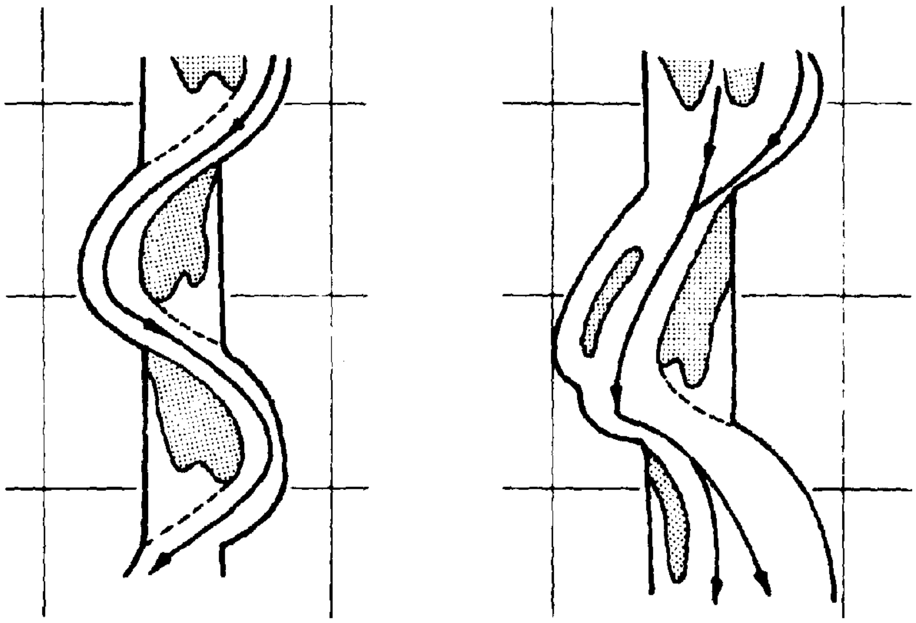


FIGURE 12 OTOE BEND MIGRATIONS



(a) Before cutoff (b) After cutoff

FIGURE 13. CHUTE CUTOFFS AT A DOWNSTREAM MIGRATING BEND [after Edgar, 1973]

On occasion, a chute cutoff formed on the upstream side of the point bar. The chute formed when the upstream limb of the bend moved downstream more rapidly than the downstream limb, thereby compressing the bend. The upstream portion of the point bar is left as the middle bar and the thalweg enlarges the channel across the lower part of the bar. The switch of the thalweg from a position above the point bar to a position through the middle of the point bar is rapid and results in a scalloping of the concave bank line opposite the point bar. The plan-view appearance of the bend after the formation of a chute cutoff is shown in Fig. 13b. The details of this type of chute formation in the laboratory have been reported by Edgar [1973].

In the CSU laboratory tests in well-graded sand, chute channels formed occasionally. Similar laboratory tests by Fiedkin [1945] in uniform sand materials produced no chute cutoffs. The two sets of laboratory tests support the hypothesis that chute cutoffs in laboratory rivers result from local differences in the erodibility of bank and bar materials caused by differences in particle sizes. We have not found any reports of field studies which indicate that chute formation by differential erosion in a downstream migrating bend occurs in natural rivers, but evidence of this process can be seen on the Fisk maps [1944].

Others

Side channels form at bends by processes which are combinations of the point bar cutoff process, the lateral migration process, and the downstream migration process. Also, it is important to recognize that the processes occurring at a bend are influenced by what is going on upstream and downstream of that bend. In fact, what is going on upstream and downstream of a bend may be the predominate reason for side channel development in that bend. For example, in the Colorado State University studies of laboratory river channel forms, the formation of a chute in one bend usually caused the pattern throughout the entire reach of laboratory channel to change. In the laboratory, these formations occurred under constant discharge conditions.

A laboratory case: In his laboratory studies, Edgar [1973] obtained backwater channels behind the point bars in a meandering-thalweg channel. The channel form evolved from an initially straight channel with a narrow, deep cross section. The first bend upstream was produced artificially. The flow eroded the concave bank of the initial bend. This eroded material entered the straight channel and deposited immediately below the initial bend of the same side of the channel as the eroding concave bank. As the deposition accumulated, more flow was forced onto the opposite bank. This impingement of the flow on the opposite bank produced a new eroding bank which soon took on the same appearance as the initial bend. The sediment from the new eroding bank deposited immediately downstream in the straight channel. This process of bank erosion and deposition was self-perpetuating in the downstream direction. The result was the meandering-thalweg channel shown in Fig. 14.

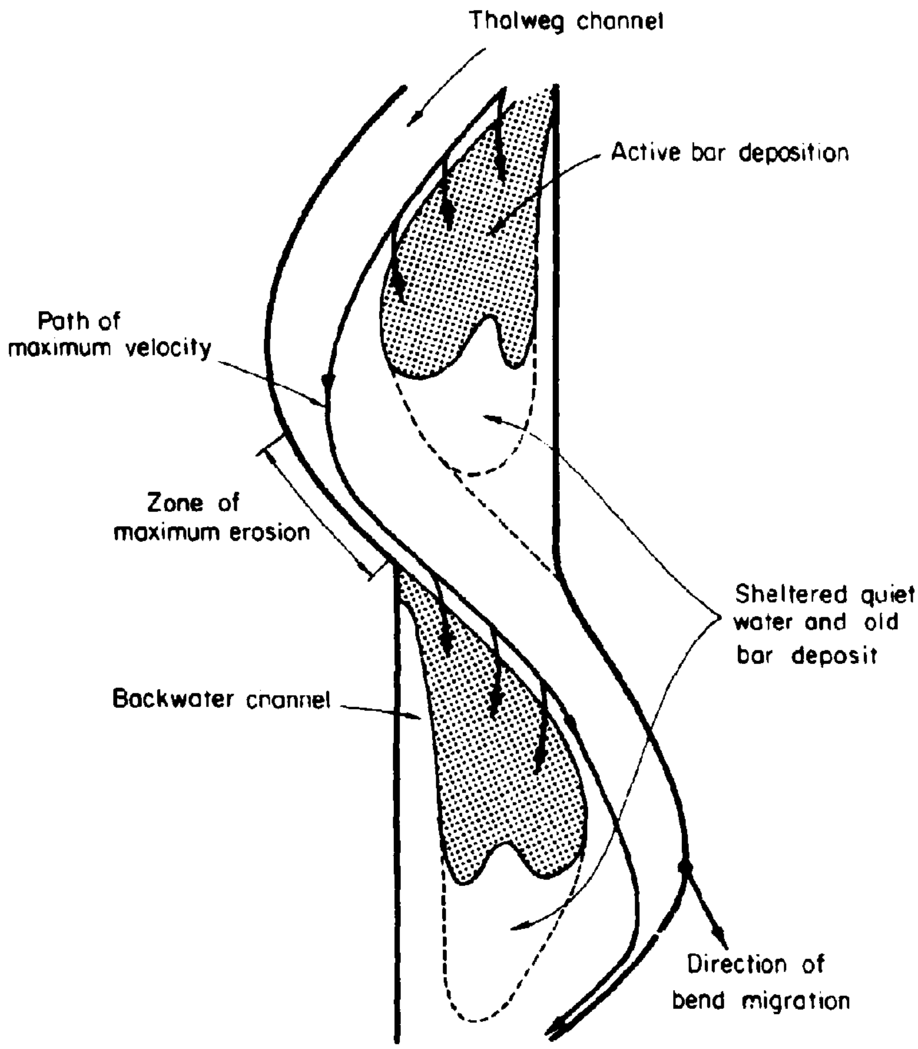


FIGURE 14 BACKWATER AREAS IN A MEANDERING-THALWEG CHANNEL [after Edgar, 1973]

The bank lines at the bends shown in Fig. 14 migrated laterally and in the downstream direction. As a consequence of this migration, the point bar moved downstream with time and an area of nondeposition formed adjacent to the inside bank. This backwater area was a residual of the original narrow, deep channel. The backwater area received only minor amounts of silt and clay sediments.

The cross section through the backwater area, the middle bar and the thalweg channel is shown in Fig. 15. The backwater area is a residual of the straight, deep, narrow channel and has been isolated from the thalweg channel by the middle bar. In Fig. 15, the thalweg channel is being forced to migrate outward to the right by the growing middle bar.

Brandywine Chute: In discussing paradoxes of the Mississippi River, Matthes [1951] described the process by which a large side channel is formed. The process

> "...has to do with the large sand bars that are commonly formed by cavings. These bars frequently build out a mile, sometimes as much as several miles, in the path of the stream, gradually forcing the river to detour by making a bend. Across such bars floods usually erode shallow swale like depressions called "chutes." Because they are dry most of the time, the chutes are inconspicuous at first, but they slowly enlarge and deepen, and in the course of time they tend to become secondary river channels that act as short-cuts for the river. The time comes when a chute ceases to be a mere overflow route for flood waters and flows water the year around. It then robs the main channel of a part of its flow, thereby causing it to deteriorate by shoaling. Eventually the chute channel takes over and becomes the main channel. The entire process is so gradual, also so commonplace, as to lack the spectacular attributes of a cutoff across a narrow neck, hence it rarely finds mention in the press. At least one important chute, named Brandywine, is in process of development at the present time [1951] some 15 miles above Memphis. It will shorten the river about five miles."

The processes by which Bradywine Chute was formed are a combination of downstream and lateral migrations coupled with the point bar cutoff process.

Cape Bend: The Cape Bend Chute (River mile 47 to 51) in the Middle Mississippi River has been in existence for at least 160 years. The bank-line configurations at Cape Bend for the years 1818, 1880, 1907, 1927, 1937, 1946 and 1969 are shown in Appendix B. Cape Bend is the bend in the lower lefthand side of the figures.

The Cape Bend configuration is controlled by rock outcrops on the right bank immediately upstream of the bend at Cape Girardeau and immediately downstream of the bend at Thebes Gap. The size of the chute has varied depending on how far the bend has migrated outward and the sequence of floods.

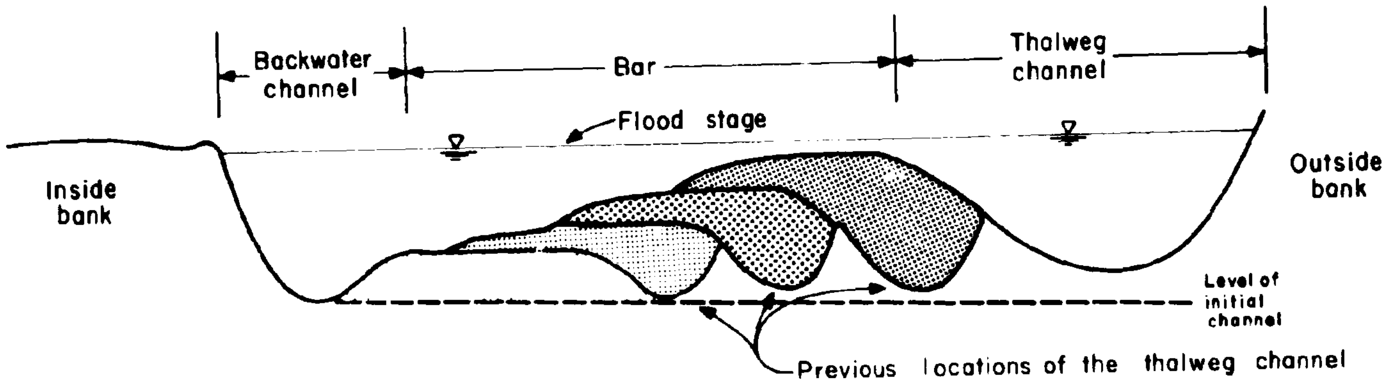


FIGURE 15 CROSS SECTION THROUGH THE BACKWATER AREA AND MAIN CHANNEL [after Edgar, 1973]

In 1818 (p.113), there was an island at the entrance to Cape Bend. The island divided the river into two channels of nearly equal width. The bend had a large radius of curvature.

In 1880 (p.115), the bend had migrated downward nearly one river width; the island had moved downstream also. The bend radius of curvature was much smaller than in 1818. In 1880, the main channel was on the inside of the bend (east of the island). This channel was twice the width of the channel on the outside of the bend.

In 1907 (p.117), the island had moved upstream from its position in 1880 and had decreased in size. The river had grown wider at Cape Bend but one-half the growth was on the inside of the bend. In 1907, the widest channel was on the inside of the bend.

The 1927 bank-line position (p.119) was the same as the 1907 position, but in 1927 the island had increased in size and was bisected by a small channel. The channel on the outside of the bend was very narrow in 1927. The main channel was on the inside of the bend.

Between 1927 and 1937 (p.121), dikes were placed in the Cape Bend reach of the Middle Mississippi River. The dikes were positioned in an effort to reduce flow in the channel on the inside of the bend and to enlarge the channel on the outside of the bend. The program has been successful in that the outside channel has been greatly enlarged. However, the 1969 bank-line map (p.124) shows that a large chute channel still exists along the inside of Cape Bend.

After studying the bank-line configuration of Cape Bend, we have concluded that there was a more-or-less stable balance of the water flows between the channels on the inside and outside of the bend when the river was in its natural state. The bend could migrate outward only so far before the inside channel would capture the flow and stop the migration. That is, although the momentum of the flow dictated the route around the outside of the bend, the route along the inside was very short and offered much less impedance to the flow. The behavior of the Cape Bend chute is somewhat analogous to that described by Friedkin [1945] who had concluded that a "...limiting width and accompanying length" exists in meandering channels.

Many of the features in the behavior of Cape Bend are alluvial. It is, however, the rock outcroppings at the right bank upstream and downstream of the bend that limit the movement of the bend.

<u>Picayune Chute</u>: The Devil's Island reach (River mile 55 to 61) of the Middle Mississippi River is that reach of river immediately above Cape Bend. For at least 160 years, Devil's Island has divided the river into a main channel on the inside of the bend and side channels on the outside of the bend. The bank-line configurations in the Devil's Island reach for the years 1818, 1880, 1907, 1927, 1937, 1946 and 1969 are shown in Appendix B.

Picayune Chute is the long narrow chute in the upper right-hand side of the 1969 bank-line configuration map (p.113). Picayune Chute originated by natural processes but has been affected by dike structures. In the photograph of Picayune Chute (Fig. 10) the remnants of a rock dike across the chute are visible.

In 1818 (p.113), an unusual condition existed in the Devil's Island reach. The river channel at the bend was divided into three channels. The main channel was on the inside of the bend. The outer two channels were chutes. The bend configuration suggests that a point bar cutoff had formed in the past.

In the period between 1818 and 1880, the channel upstream of the bend shifted to the west (left) one-half a river width and became braided. In 1880 (p.115), the main channel on the inside of the bend was much larger than in 1818. One of the side channels on the outside of the bend had remained about the same size and the other had decreased greatly in size.

By 1907, a large island had developed in the main channel. Otherwise the 1907 bank line (p.117), was nearly the same as the 1880 bank line. The side channels on the outside of the bend had become backwater channels by 1907. Picayune Chute took on the appearance that it still has today. The other side channel on the outside of the bend lost its intake and became an appendage. Between 1880 and 1907, a long narrow area was added to the upstream end of Devil's Island.

By 1927 (p.119), the large island on the inside of the bend had become attached to the Missouri mainland. The main channel remained on the inside of the bend but had been displaced to the east and had become narrower. The upper section of Devil's Island was disected by channels. The lower reach of Picayune Chute remained unchanged. The appendages on the outside of the bend continued to deteriorate.

The first dike was placed in the Devil's Island reach in 1894, but the reach was hardly affected by structures until a large program of dike construction was carried out between 1927 and 1937. In 1937 (p.121) the bank line was somewhat controlled by dikes.

It seems that behavior of the Devil's Island reach was controlled primarily by the westward movement of the upstream reach of river. Picayune Chute was in the favorable position to obtain clear water at its intake and therefore to retain its channel cross section fairly well. Moreover, the large expanse of Devil's Island isolated the backwater channel from the main channel. In its natural state the Devil's Island reach did not behave in the manner of most alluvial bends. Usually, the main channel is on the outside of the bend and the islands and side channels are on the inside. Usually a bend with the configuration of the Devil's Island reach migrates downstream. The outside of the bend in the Devil's Island reach has been a depositional area.

SUMMARY

In its natural state, an alluvial river divides itself into two or more channels by the processes of either erosion or deposition. The side channels so formed can grow in size and capture most of the discharge and become the main channel; they can deteriorate in size and become a part of the floodplain; or they can grow to the size of the main channel and maintain that size. In the natural state, those side channels which are obliterated by deposition are replaced by new side channels caused by floods and/or river migrations.

In the Middle Mississippi, the river is no longer free to migrate and produce new side channels. There are no meander loops to be cutoff by floods. Except for the major chute channels, natural side channels in the Middle Mississippi River are being filled with sediment. The major chute channels such as Cape Bend have achieved a size which indicates they could exist for a long period of time.

In the absence of further man-induced changes in the hydrology or geomorphology of the Middle Mississippi River, all natural side channels except major chutes, may disappear from the river scene. Within 100 to 200 years, even Picayune Chute will fill. There will be no natural replacement side channels. The preservation of existing side channels should be considered in planning future contraction works in order to maximize environmental benefits and minimize flood stages.

MAN-MADE SIDE CHANNELS

INTRODUCTION

Today most of the more recent side channels in the Middle Mississippi River are man-made. These side channels form in and along the dike systems employed to improve the river navigation channel. Dike fields are projected into the river channel to contract the river width at low-flow. In the contracted form, the river thalweg remains in approximately the same low-flow position every year. Moreover, low-flow depths in the contracted river are deeper than in the broad natural channel.

The contraction of the Middle Mississippi River with dikes has eliminated most of the natural side channels. In many cases, these natural side channels have been replaced with new man-made side channels which may be more favorable habitats. It may be beneficial to the river ecology to retain and maintain man-made side channels as well as the natural side channels. The main problem is that the life of a side channel produced by dike fields is usually relatively short. The dike fields and the side channels fill with sediment rapidly because dike fields are usually located in areas of natural deposition. Once the side channel is filled with sediment, there is easy access to the island area. In many cases, the filled side channel area and island area are converted to agricultural use. Thus, the areas are no longer suitable as fish and wildlife habitats. Cleared areas provide less resistance to high flows than treed areas and are more useful in passing large flows at lower stages.

The life history of side channels and dike fields is evident in all reaches of the Middle Mississippi River. Dikes were built in the Middle Mississippi after the 19th century. In almost every reach, there are old dike fields completely covered by sediment and vegetation, and now undistinguishable from the mainland; there are new and old dikes visible only where they cross backwater channels and at the main channel extremity; and there are new dike fields as yet not covered by sediments and vegetation. A side channel in a dike field passes through stages of development usually to a stage where the side channel is undistinguishable from the adjacent floodplain.

EVOLUTION

The Single Dike

When a dike is projected out from one bank into the channel flow, the flow velocities are increased, especially around the nose of the dike. These increased velocities scour sand from the region around the nose of the dike. Because the bed velocities at the nose of the dike are still less than the surface velocities, it is the sediment-laden bed velocities that make the turn into the lee side of the dike. In the lee side of dikes placed in natural depositional areas, where the flow expands again, the sediments are deposited. Figure 16 is a photograph of a bar formed downstream of a dike projected two feet out from

FIGURE 16 BAR DOWNSTREAM OF A DIKE

the bank of a six-foot wide straight laboratory channel. The direction of flow is from the bottom to the top of the photograph. The texture of the sand on the bar identifies the bar and the direction of flow on the bar.

The scour hole on Fig. 16 is much smaller in volume than the bar behind the dike. After the scour hole has reached an equilibrium depth, the flow field around the nose of the dike takes the normal bed materials moving in from above the dike and places these sediments on the bar. Thus in the model, the bar continues to grow, even after the scour hole has ceased growing.

As soon as the bar is formed, a derelict channel is left in the area between the bar and the bank line. This channel accepts the flow over the bar and drains that flow out the lower end. If the bar were to become vegetated or otherwise stabilized, the small channel between the bar and the right bank (right side of the photograph) would become a side channel. The future of the side channel would depend on river alignment, discharge and sediment transport.

The projection of the single two-foot long dike into the six-foot wide channel produced a scour hole in the channel bed at the nose of the dike and a sandbar downstream of the dike. This single dike did not produce any general degradation of the channel bed on the side opposite the dike. The vortex flow system set up around the nose of the dike was capable of passing enough water through the scour hole so that there were no increases in velocities on the opposite bank. Because velocities on the opposite bank were not increased, the bed level on that side remained the same.

If left to evolve further, the bar shown in Fig. 16 would continue to move into the area occupied by the small channel until the channel became obliterated. The channel would be closed by sand avalanching over the crest of the bar and into the channel. The upper part of the small channel would close first, and thereafter closure would progress downstream. A calm backwater area would remain on the immediate lee side of the dike. After development, the level of the bar surface would be nearly equal to the flow stage that produced the bar.

The crest of the dike shown in Fig. 16 was constructed so that flood flows passed over the crest but low flows did not. The height of the dike has an important influence on the buildup of the bar. If the dike crest is at the same elevation as the bed, no bar forms. As we increase the elevation of the crest, more and more flow must pass around the nose. Once the crest elevation is greater than the high-water level, the crest elevation has no more incremental effect on the flow. A dike with a higher crest level produces a shorter bar more rapidly than the intermediate level dike shown in Fig. 16. Also, with the high dike and favorable upstream depositional conditions, the small channel fills more rapidly.

The effect of changing the flood level in the laboratory model is opposite to that of changing the dike crest levels. Lower flood levels result in shorter bars and in a more rapidly filling small channel.

Dike Fields

If we add another dike on the same side of the channel downstream of the single dike shown in Fig. 16, the bar building processes change significantly. The first effect is that much less flow enters into the region between the two dikes and more flow passes in the contracted section. The second dike blocks the discharge of the small channel along the bank. Less water and sediment enter into the region between the dikes. The net result is that the bar between the dikes grows and moves inward much more slowly than when there was only a single dike.

In the model, the addition of the second dike is usually sufficient to cause a general degradation of the channel on the opposite side. The degradation causes a lowering of low-water levels which could leave the small channel dry during periods of low flow.

The evolution of the forms within the dike fields in a straight stretch of laboratory river are illustrated in Fig. 17. Flow was from the bottom to the top of the photographs. The three model dikes were constructed so as to be submerged during floods but exposed at low flow.

The photograph in Fig. 17a was taken after repeated hydrographs failed to move any more sand onto the bars between the dikes. The combination of flow over the dikes and blockage of the discharge in the side channel by the downstream dikes produced small bars and relatively large channels in the dike field.

In order to prolong the evolution of this dike field morphology, the elevation of the upstream dike crest was raised to a level above the flood level. The elevated lead dike is shown in place in Figs. 17a, 17b, and 17c. Immediately the bars enlarged and moved bankward decreasing the size of the channel along the bank. The photograph in Fig. 17b shows the change in bar size after the lead dike crest elevation was increased.

When the enlargement of the bar ceased before the channel along the bank filled a notch was cut in the middle dike at the bank line (see Fig. 17b). The notch permitted increased flow over the upstream bar which in turn built rapidly bankward. There was no increase in flow over the downstream bar, but the channel below the notch filled with sediment carried in from above. Soon the entire region in the dike field was filled with sediment as shown in Fig. 17c.

a. Lead dike crest is raised

b. Center dike is notched

c. Side channel is filled

FIGURE 17 EVOLUTION OF BARS IN A DIKE FIELD

The dike field performed admirably in terms of forming a deep, low-water main channel. The cross sections of the main channel in the dike field reach and in the reach above the dike field are shown in Figs. 18a and 18b. The vertical scale exaggeration in Fig. 18 is five. The low-water channel was about twice as deep opposite the dike field as it was upstream of the dike field. There was no overbank flow in the model.

An overlay of the cross section shown in Figs. 18a and 18b is made in Fig. 18c. The portion of the cross section which was degraded by the presence of the dike field is shaded dark grey. The deposition portion of the cross section between the dikes is shaded light grey. The cross-sectional area with deposition was much larger than the area scoured. The material in the deposition areas came from the low-water channel and from that carried by the river into the contracted reach. Once the model dike field filled with sediment, the contraction had no measurable effect on sediment transport in the model.

In Fig. 18a we can see that the dike field has narrowed the entire river channel except at stages above bank-full stage. The small channel and the surface of the bar were dry most of the time.

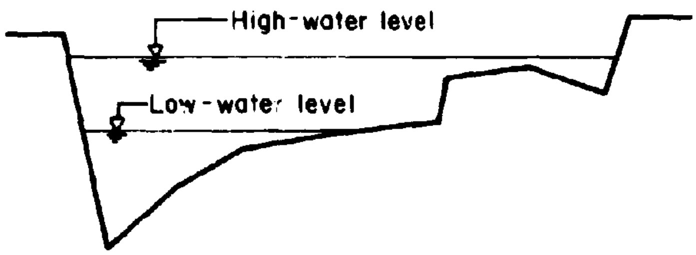
Vegetation

There is one important difference between the evolution which occurred in the laboratory model dike field described above, and the evolution which occurs in dike fields in the Middle Mississippi River. In the Mississippi River vegetation becomes established on the surface of bars and alters the evolution.

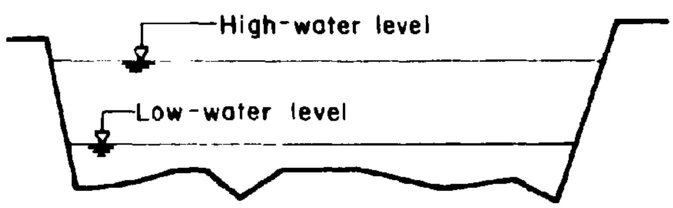
We have studied the effect of vegetation on the evolution of bars and channels in laboratory dike fields. Fig. 19 is a photograph of a vegetated bar immediately downstream of a single dike. This is the same bar as that shown in Fig. 16. Immediately after the photograph in Fig. 16 was taken, small white plastic trees (shown in Fig. 19) were added to the crest of the bar. The trees impeded the flow across the top of the bar and effectively stopped the movement of the sand into the small channel along the bank line. With the addition of trees, the bar became an island and the small channel became a side channel.

The addition of dike fields in the reaches of laboratory river upstream and downstream of the single dike resulted in a gradual degradation of the riverbed. As the bed degraded, the low-water stage in each succeeding hydrograph became lower and more of the island became exposed. As parts of the island became exposed, more trees were added; first the dark green trees and afterwards the green and white trees. Thus, the trees reflect different stages of bar development.

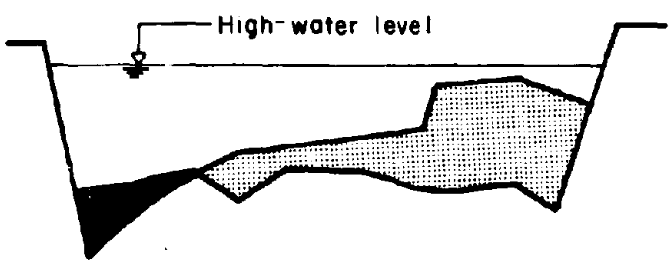
In the case of the single dike, the addition of vegetation to the bar helped preserve the life of the side channel by stopping the movements of large amount of bed sediments over the bar. Sedimentation still occurred in the backwater channel but at a very much reduced rate. The sedimentation resulted from the settling out of silts and clays carried in suspension. In the laboratory this layer of silt and



a. Cross section at the dike field



b. Cross section upstream



c. Areas of erosion and deposition

FIGURE 18 CROSS SECTIONS AT AND ABOVE THE MODEL DIKE FIELD

FIGURE 19 VEGETATION ON A BAR

clay in the backwater channel was perceptible by eye but could not be measured.

High-Water Levels

If trees are placed on the bars in the dike fields shown in Fig. 17, there would be very little flow through the bar area. The reduction in cross-sectional area at bank-full stage caused by the dike field and the vegetation on the deposits in the dike field is illustrated in Fig. 20. For example, in the laboratory model, the cross-sectional area at bank-full stage in the contracted reach was 1.1 square feet whereas in the natural channel upstream, the area was 1.8 square feet. Hence, for a given high-water discharge, stages are higher in the contracted reach than in the broad natural channel.

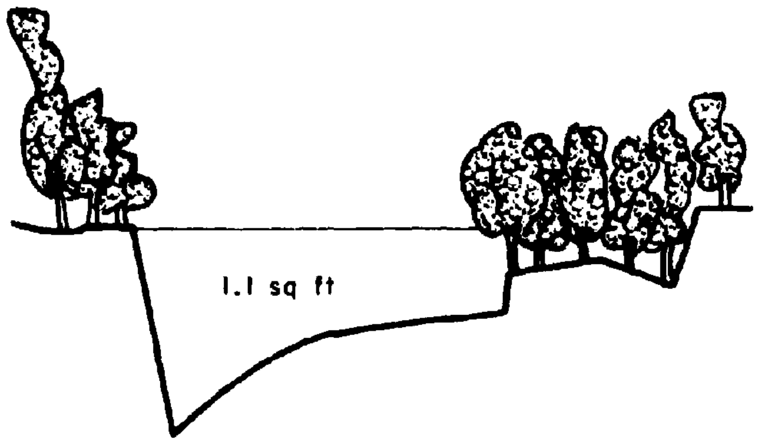
Field Cases

The features of the bars and the behavior of sediment and water in laboratory channels with dike fields and vegetation are essentially the same as those in the Middle Mississippi River. The photograph in Fig. 21 illustrates the various stages of side channel development in the Middle Mississippi River dike fields. The long bar at the bottom of the photograph is new; small dunes can be seen on its surface. The bar was formed by the extensions of the rock dikes. The two older pile dikes that extend only a fraction of the distance to the main channel are not effective. The channel between the bar and the vegetation is wide and shallow and has a sand bed.

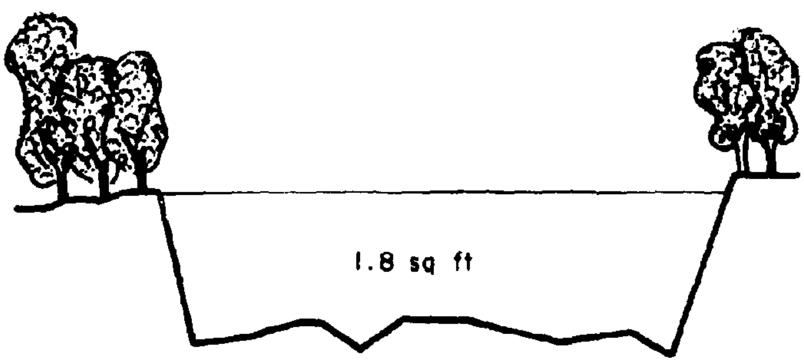
The backwater channel in the bottom left side of Fig. 21 is a mature side channel formed by previous dike fields. The island between this old channel and the new channel is well vegetated. There are two trees growing on the dike that is still visible across the lower end of the backwater channel. Immediately downstream of this dike, we can see evidence in the vegetation that the downstream extension of this side channel has been completely filled with sediment and covered by vegetation.

The rates of sedimentation between the dikes is very rapid immediately after the dikes are built. The local scour at the nose of the dikes supplies the initial sediments; thereafter the bar building materials are bed sediments carried along by the river flows. When the bar becomes vegetated, sediment-laden bed currents no longer flow over the bar. Then the sedimentation results from the settling out of the suspended sediments from the slow-moving currents. The rate of sedimentation is reduced to about one to three feet per year. The major portion of these sediments is fine sand.

Later, the side channel becomes isolated from the main channel by a dense growth of vegetation. Very little water flows in the side channel because the path through the side channel is much more resistant to flow than in the main channel. The side channel has become a backwater channel. The bed and banks of this channel and the surface of the island are covered with mud which settles out from the slack water



a. Contracted flood channel



b. Natural flood channel

FIGURE 20 COMPARISON OF FLOOD CHANNEL AREAS

FIGURE 21 DIKE FIELDS IN THE MISSISSIPPI RIVER

that enters the side channel and covers the island during floods. This side channel is slowly deteriorating in size due to the yearly deposition of mud; the rate of deposition is in the order of one to five inches per year in the Middle Mississippi.

The ultimate fate of a mature side channel is obliteration by filling with sediments. The last phase is short in duration when vegetation can encroach on the side channel.

Once the side channels have filled, the plan-view appearance of the river at all stages is the same as that of a straight and deep natural river. The hydraulics of this new river are different than before the introduction of dikes. This new river geometry is not considered permanent however. The experiences in the Middle Mississippi River are that the annual maintenance on dikes is substantial. This is the maintenance associated with present day contraction and with the ice conditions and the modest flood flows that have occurred in the last two decades.

MAINTENANCE OF SIDE CHANNELS

As a result of both natural and man-induced changes, numerous side channels exist within the St. Louis District. It is being determined if these side channels provide desirable fish and waterfowl habitats as long as they can be kept open. Because of the supposed value of these channels to the aquatic, marsh and terrestrial biota along the river, it may be desirable to keep such channels productive by preventing major sediment deposition therein.

In the absence of rare natural events, nearly all natural and man-induced side channels should completely fill with sediment unless something is done to maintain side channels. The rates of sedimentation vary greatly. Large chute channels can remain open for a century or may fill very rapidly depending on each situation. For example, in the Powers Island reach shown in Fig. 22, there were six islands in the seven mile reach in 1884. The river has been contracted with dike fields and all the chutes but one have disappeared, as the 1968 hydrographic survey shows. That remaining side channel is now Santa Fe Chute. It is closed by a dike at the inlet and a partial dike at the outlet. Yet the side channel has not filled in with sediments and has retained its status for at least 90 years.

The geometry of the Santa Fe Chute in 1884 and 1968 is given in Table VII.

TABLE VII

GEOMETRY OF SANTA FE CHUTE

	1884	1968
Surface area	0.68 sq mi	0.73 sq mi
Length	2.85 mi	3.90 mi
Average width	1270 ft	990 ft

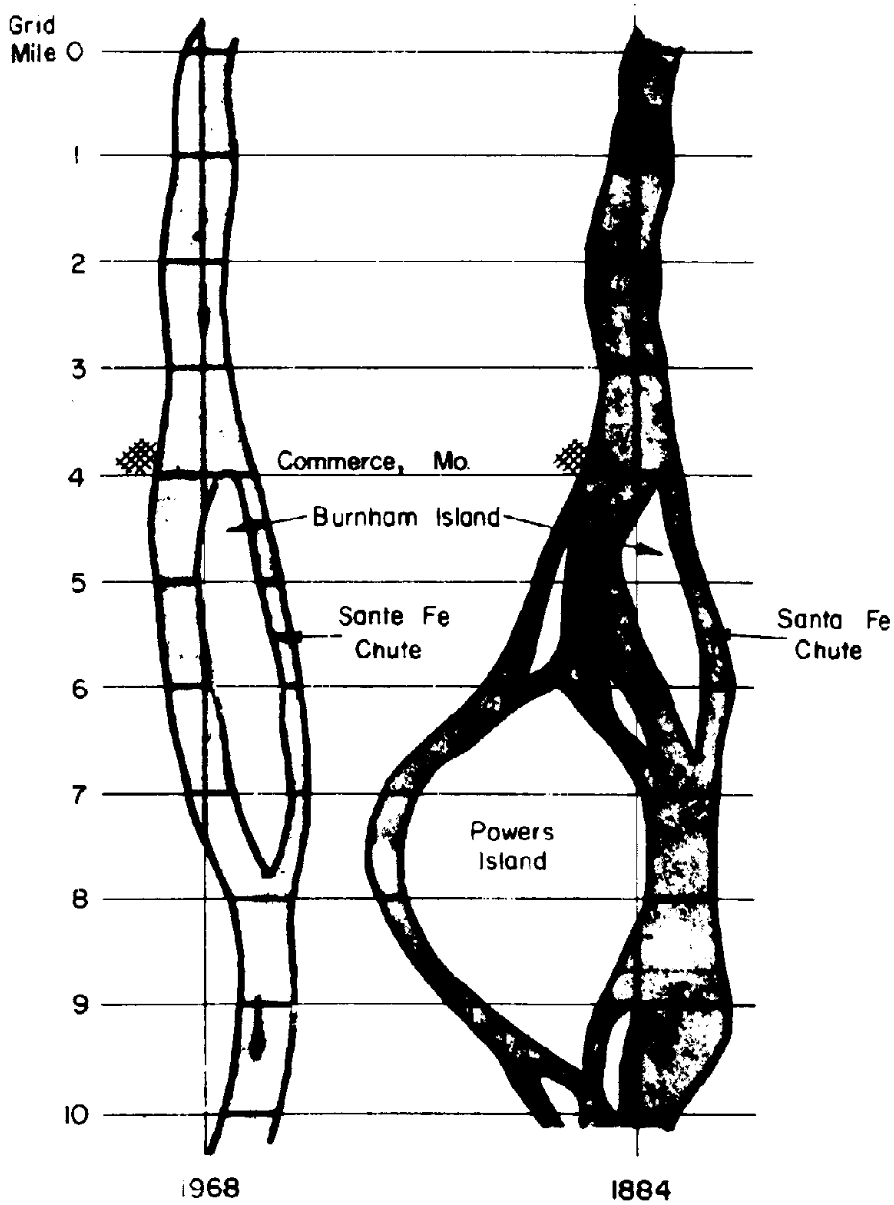


FIGURE 22 LOSS OF CHUTE CHANNELS NEAR POWERS ISLAND

Since 1927, concern has been principally with the navigation problem in the Middle Mississippi River. It is now necessary to consider the impacts of river contraction on the natural environment and on the flood protection system. The value of the side channels as habitats for aquatic marsh and terrestrial biota must be considered. One concludes that in most cases, side channels are transient features of the riverscape. They form and then are modified, and finally are obliterated by deposition. We have studied different ways of extending the life of side channels, hope is that future engineering works can be designed which will serve all interests in the Middle Mississippi River.

Notched-Dike Side Channel

Solid lead dike: In the CSU laboratory studies of the dike fields shown in Fig.17, the notch resulted in the rapid sedimentation in the entire dike field. In subsequent tests, a notch was cut in the lower dike as well. With the additional notch we were able to obtain and maintain a side channel in the dike field. The dike field, the islands and the side channel are shown in Fig. 23.

The side channel produced by the solid lead dike and the two notched dikes consisted of a series of scour holes immediately downstream of each dike at the bank-line terminal. Such scour holes would produce bank-line failures along the side channel if the bank lines were not stabilized. In the model, this bank line was constructed with a sand-cement mix. During floods, the side channel was supplied a small amount of clear water flowing over the solid lead dike and a large amount which came around the nose of the lead dike, across the bar along the edge of the trees, across the crest of the second dike and then into the side channel (see Fig. 23). During periods of low flow the side channel was a slack water area. Cross sections through the main channel, the island and the side channel are shown in Fig. 24 along with the water surface and bed level profiles along the side channel. The vertical scale exaggeration in Fig. 24 is ten.

During floods and intermediate flows, the side channel receives sediments carried by the flow around the nose of the dike, but the amounts were not large. These sediments were carried on through the dike system. At low flow the side channel area received no sediments.

The white trees in Fig. 23 were planted on the crest of the bars at an early stage of development. The trees arrested the movement of the bars into the side channel area. The red and white trees were added at intermediate stages of development. In the latter portion of the experiment, no new trees were added. The exposed sandbars in the side channel were not part of the bar moving in from the main channel, but were the result of scour below the notches during floods.

Notched lead dike: The side channel formed by a solid lead dike and two notched dikes in a straight reach of channel maintained its channel form well. Improvements in the size of the side channel can be made by notching the lead dike also. The resulting dike field morphology

FIGURE 23 NOTCHED-DIKE SIDE CHANNEL

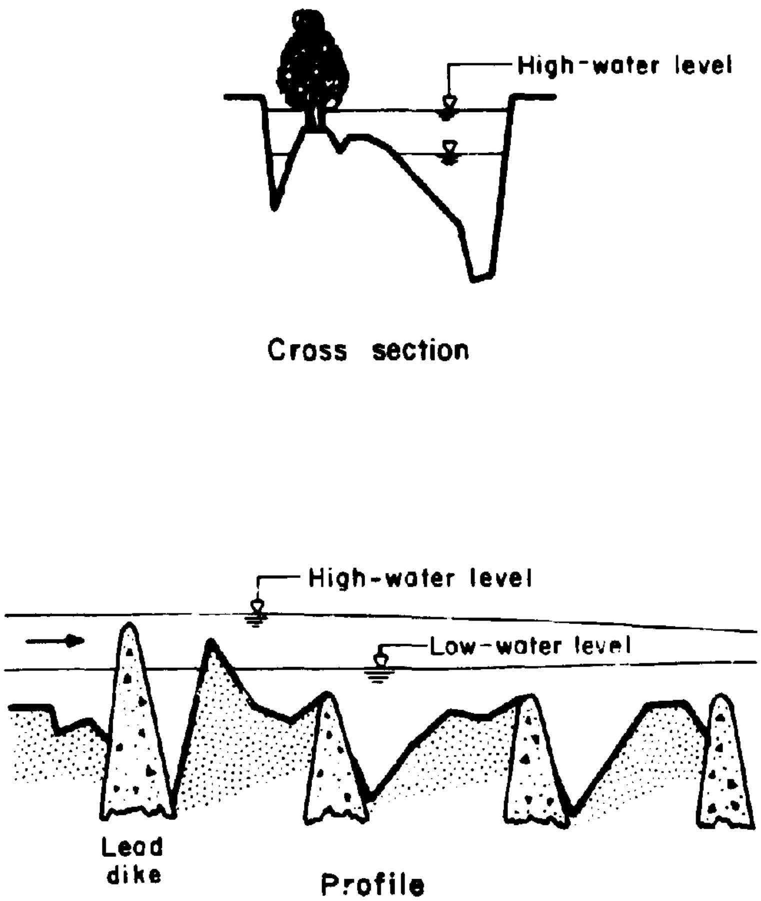


FIGURE 24 CROSS SECTION AND PROFILE
NOTCHED-DIKE SIDE CHANNEL

is shown in Fig. 25. The upper dike in the photograph is the notched lead dike. Below the lead dike there are two notched dikes shown in Fig. 25, and a third dike not visible in the photograph.

The notched lead dike allowed a large amount of clear water into the side channel; so much water that flow was from the side channel to the main channel in later stages of development. The islands were dissected with small channels leading from the side channel to the main channel. The islands adjacent to the main channel were aligned with the main channel. In the case of the solid lead dike, the islands were aligned in a direction leading from the main channel to the side channel. The islands adjacent to the inner channel in the all notched-dike field (Fig. 25) were formed from materials scoured out below the notches in the dikes. A cross-sectional view of the main channel, the islands, and the side channel is shown in Fig. 26. Also the water surface and bed level profile of the side channel are given in Fig. 26. The side channel receives its water from the main channel at the lead dike notch at all river stages.

Curved channel: In laboratory experiments on dike fields in straight reaches of river, we were able to maintain side channels by notching dikes. In similar experiments with a curved reach of river, we were not.

The principal problem in obtaining and maintaining a side channel in a dike field on the inside of a bend are two-fold. First, the inside of a bend is a natural depositional area, and second, with or without a dike field the inside of a bend is usually dry during low flow.

At the start of the experiment with a curved laboratory river channel, the riverbed was made level in the transverse direction. A solid lead dike and three notched dikes were placed on the inside of the bend. The crest level of all dikes were such that flood flows submerged the crest and low flows did not.

After eight hydrographs the bar between the lead dike and the second dike had filled in the small channel to the crest level of the notch in the second dike. The bar looked exactly the same as that shown in Fig. 17b. After eight more hydrographs, the region between the second and third dikes became filled. Below the third dike in the bend, very small bars formed at the main channel extremities of the dikes. On the downstream end of the bend, the flow had been completely channelized on the outside of the bend by the upstream dikes. No trees were placed on the bars until the channel through the notches was filled with sediment. For each hydrograph, the flow rate in the model was varied between 0.25 and 1.5 cfs in a manner so as to reproduce the form of the yearly flow duration curve in the Middle Mississippi River.

The cross section through the main channel, the island and the side channel between the lead and second dikes is shown in Fig. 27.

FIGURE 25 ALL NOTCHED-DIKE SIDE CHANNEL

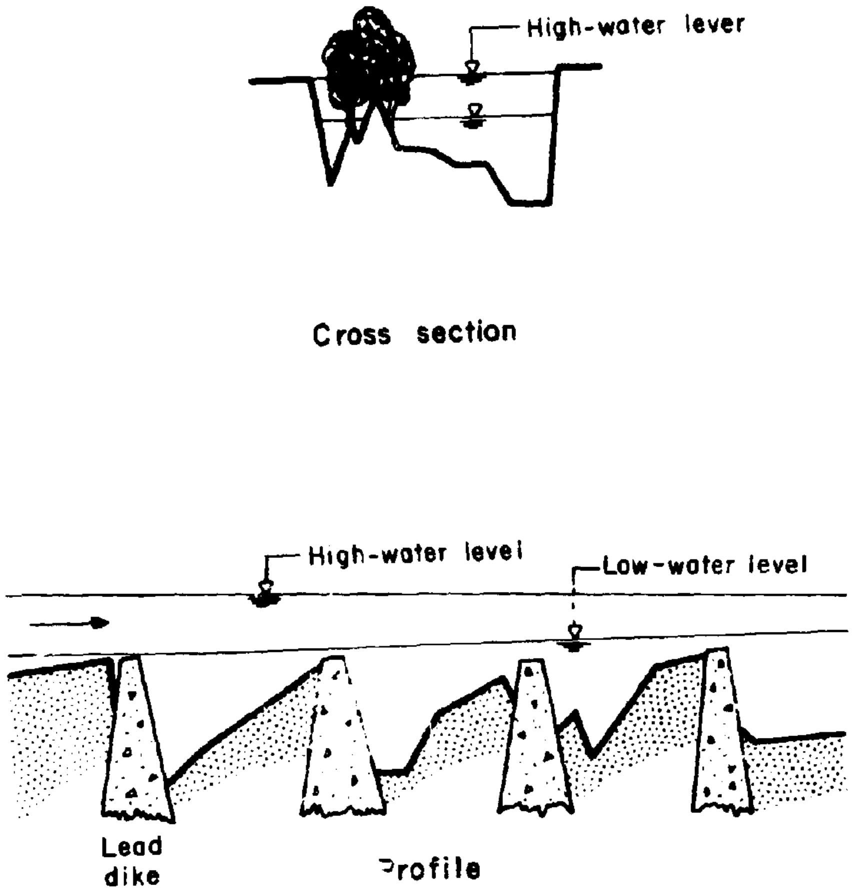


FIGURE 26 CROSS SECTION AND PROFILE
ALL NOTCHED-DIKE SIDE CHANNEL

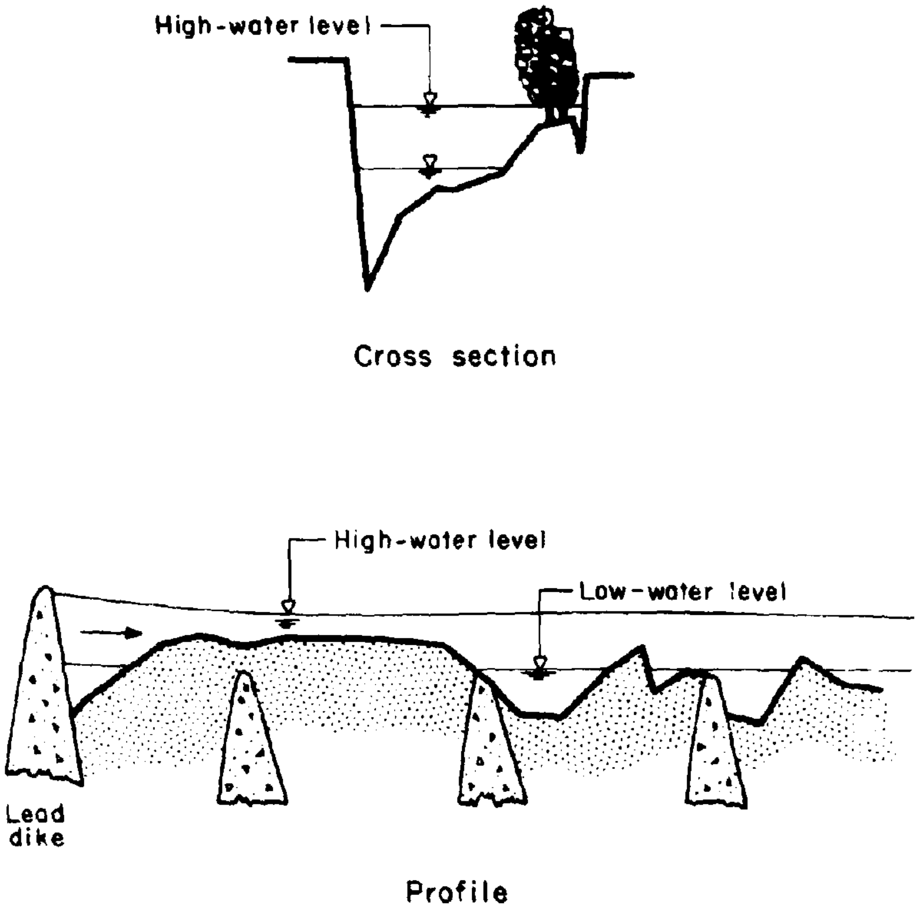


FIGURE 27 CROSS SECTION AND PROFILE
RIVER BEND SIDE CHANNEL

The dike field resulted in degradation around the outside of the bend. The degradation was so great that the high-water stage level dropped below the level of the solid lead dike. The side channel received small amounts of water from around the nose of the lead dike during floods and was dry during low flows. The water surface and bed level profile along the side channel in the bend are shown in Fig. 27.

In the model river bend, the short life span of the side channel along the inside of the bend was a result of a combination of three factors. The first was the large amount of degradation which lowered high-water stages as well as low-water stages. The second was the fact that no clear water was available to the side channel; the side channel received small amounts of sediment-laden water from around the nose of the lead dike. The third was the lack of vegetation on the bars which allowed more sediment-laden water to enter the side channel.

Rejuvenator Dike

Once the side channel along the inside of the bend had filled with sediment, an attempt was made to flush the sediments out of the side channel. A rejuvenator dike was constructed in the straight approach section to the bend immediately downstream of the solid lead dike. The rejuvenator dike was built from the high point on the island out past the main channel terminal of the lead dike and into the main channel. The rejuvenator dike is the rock dike immediately downstream of the large yellow lead dike in Fig. 28. The filled side channel is immediately to the right of the island shown in Fig. 28. The area between the rejuvenator dike and the lead dike was the inlet to the filled side channel. The photograph in Fig. 28 was taken at low flow; there was no water in the side channel.

The intake formed by the rejuvenator dike was in a favorable location to receive clear water because the intake was located in a region where the streamlines were being diverted across the channel by the lead dike. The rejuvenator dike diverted much water into the side channel during floods; however, the water carried with it large amounts of sediment which were deposited as a bar in the intake. Most of the water entering the side channel did not flow along the side channel but made its way over the island back to the main channel. Materials were scoured from the tops of the islands, but no degradation occurred in the side channels. A cross section through the main channel, the island and the side channel between the rejuvenator dike and the first notched dike is given in Fig. 29. The dark-shaded areas are areas scoured by the presence of the rejuvenator dike. The light-grey area is the area of deposition.

The model rejuvenator dike was a failure in that its presence did not rejuvenate the side channel. No degradation occurred in the side channel and the inlet to the side channel was being filled rapidly with sediment. In order to receive clear water with very little sediment the intake must be aligned with the velocity field in the main channel. In Fig. 28, the axis of the rejuvenator dike is normal to the main channel velocity field. That alignment

FIGURE 28 THE REJUVENATOR DIKE

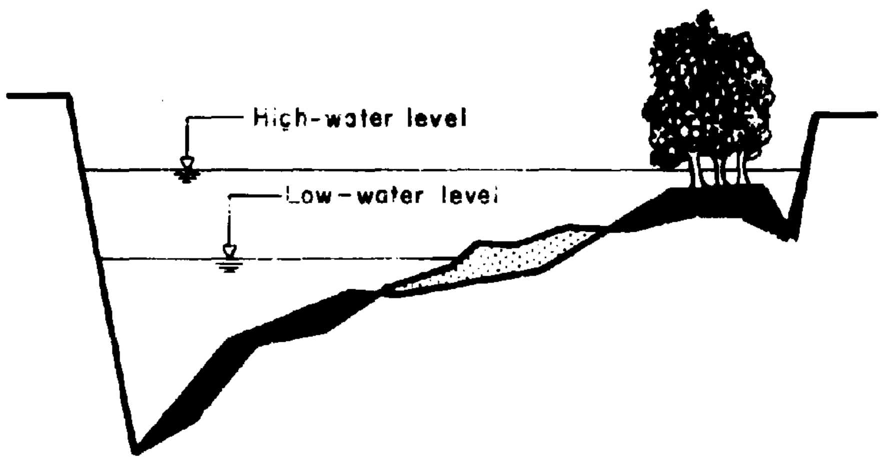


FIGURE 29 CROSS SECTION BELOW THE REJUVENATOR DIKE

could be obtained by making the bank-line terminal of the rejuvenator dike at the notch on the first dike below the lead dike. The main channel terminal would be the same as that shown on Fig. 28. In the dike fields shown in Fig. 17, a rejuvenator dike was constructed out into the main channel in a position and alignment to receive clear water with very little sediment. The water was discharged into the sediment clogged side channel. The clear water scoured sediments from the side channel and produced a rejuvenated side channel. The problem with this rejuvenator dike was that constant repair work was needed because main channel flows were destroying the rejuvenator dike.

Short Extensions

Much of the dike construction plan for the Middle Mississippi River navigation improvement project will be short extensions of existing dikes. Field experience in the Middle Mississippi River and model experiments show that short extensions of existing dikes into the main channel do not result in new side channels. An extension of a few hundred feet would be a short extension.

The short extension of a dike field in natural depositional areas results in the formation of long low bars between the dikes and a very shallow channel between the bars and the bank. The entire area of the dike fields remains as sand if the dike extension crests are low and becomes vegetated if the dike extensions are high in elevation.

If the area of the dike field becomes vegetated, a portion of the high-water carrying capacity of the river is lost. That newly vegetated area is not as effective in carrying high-water flows as it was prior to becoming vegetated. Then, in general, short extensions of existing dikes will produce a deeper low-water channel, no new side channels, and higher stages during floods.

SUMMARY

In laboratory studies we were successful in obtaining and maintaining side channels in dike fields under these conditions:

1. The bed elevation of the region where dikes are to be placed must be below the low-water level. Otherwise, the side channel will be dry at low flow.

2. If there is to be flow at all stages in the side channel, the intake of the side channel must receive no more than its fair share of the sediment load carried by the river.

3. If the side channel is isolated from the main channel by large heavily vegetated islands and a high solid lead dike the side channel becomes a slack water area which has a long life similar to that of Picayne Chute.

The outlook to obtaining and preserving side channels in the Middle Mississippi River by designing suitable structures in the dike fields is not good.

In the Middle Mississippi River, dike fields are usually placed in natural depositional areas such as the insides of bends. The bed elevations in these areas are greater than the low-water stages. Any side channels formed in such areas will be dry for a portion of the year.

In nearly all field situations the inlet to the side channel formed by dike fields is located in a position to obtain more than its fair share of sediment. Generally speaking, the life of such side channels will be increased if these intakes are closed soon after the side channels form.

It is possible to realign the river so that the intake to a side channel is in a favorable position and alignment to obtain clear water and very little sediment. Realigning the river to form a favorable offtake is possible but would require massive structures to resist the forces of the main channel currents. An alternative would be to realign the entire river with standard dikes. It is speculated that realigning the river by either of these structures would be very expensive.

The notched dike may help in extending the life of very few side channels. In general, the notched dike cannot be located in the proper position in the flow field. Also, bank-line instability results where large scour holes at notches occur next to the bank line.

As dike fields result in the lowering of the low and intermediate water stages, it is anticipated that groundwater levels in the aquifers connected to the river will decrease. Also some degradation in the tributary channels which flood while the main channel is at low stage should be anticipated.

CONCLUSIONS

From our analysis of the historical changes in the river and from our geomorphic model studies, we have come to the following conclusions concerning the planned channel contractions by extending existing dikes and building new dikes to achieve a 9-foot deep low-water navigation channel in the Middle Mississippi River. It is assumed that the dikes will be built to the same specifications that have been used in the last decade and that vegetation will form on the bars in the dike fields. Below, the anticipated river behavior is compared to the behavior of the river as it is in 1973. In this way, the comparison can be made without considering levees. The levees were completed prior to 1973.

1. The natural backwater channels are a product of the natural, uncontrolled, shifting river. Any river subject to development will experience a deterioration of the natural backwater channels unless these channels are maintained artificially.

2. Future channel contractions will result in an increase in the depth of flow at all river stages.

3. Future channel contractions will decrease the river channel capacity at flood stage. The result will be higher flood stages for a given flood discharge.

4. Future channel contractions will lower the riverbed level and the low and intermediate water stages in the river. Stages will be lower on a greater number of days in the year. Lower stages affect groundwater levels in the aquifers connected to the river and affect tributary channels.

5. In the past, the construction of the dike fields has eliminated many natural side channels but these natural side channels were replaced by side channels resulting from the dike fields.

6. In the most part, future channel contractions by extensions of dikes will produce no new side channels.

7. Unless steps are taken to prevent it, ultimately nearly all natural and man-induced side channels should completely fill with sediment and become undistinguishable from the floodplain.

8. Small natural and man-made chute channels fill at a rate of up to three feet per year. Backwater channels fill at rates between one and five inches per year. Those few large natural chute channels in existence today will remain open for a long period of time.

9. Generally speaking, it is very difficult to design dike fields so that the resulting side channels will be self-maintaining. Dike fields are usually located in depositional areas of the

river channel and suitable side channel intake positions are not available unless the flow is realigned upstream of the dike fields.

10. The life of a side channel can be increased greatly if the side channel can be isolated on the upper end from the main channel. When the side channel is isolated in this manner, the side channel is a backwater channel and the rate of sedimentation is very small.

11. Blocking an unsuitable upstream intake to a side channel will extend the life of that side channel. With the upstream intake blocked, the sediment supply to the side channel is reduced. Short ride channels can be supplied with water during low stages from the lower end.

12. The notched dike may help in extending the life of a very few side channels. In general, the notched dike cannot be located in the proper position. Also, bank-line instability will result where large scour holes occur next to the bank line.

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APPENDIX A

MIDDLE MISSISSIPPI RIVER BANK LINES

IN

1880 AND 1968

The bank-line maps identified as 1880 were prepared from 1:20,000 scale hydrographic survey maps made under the direction of the Mississippi River Commission between 1876 and 1881.

The bank-line maps* identified as 1968 were prepared from mosaics of aerial photographs taken in November, 1967 (Miles 149-170) and March, 1968 (Miles 0-148). The mosaics were a part of the hydrographic survey maps dated 1970. The survey maps are titled "Hydrographic Survey Maps of the Mississippi River, Mouth of the Ohio River, Mile 0 to Mile 300, U.S. Army Engineer District, St. Louis, Corps of Engineers, St. Louis, Missouri."

The grid on the 1968 photographs and the latitude and longitude lines on the 1880 maps did not agree in the Kaskaskia Island and Devil's Island reaches. In these reaches, we made adjustments to the 1968 grid and river bank line to facilitate matching the bank lines to reaches above and below.

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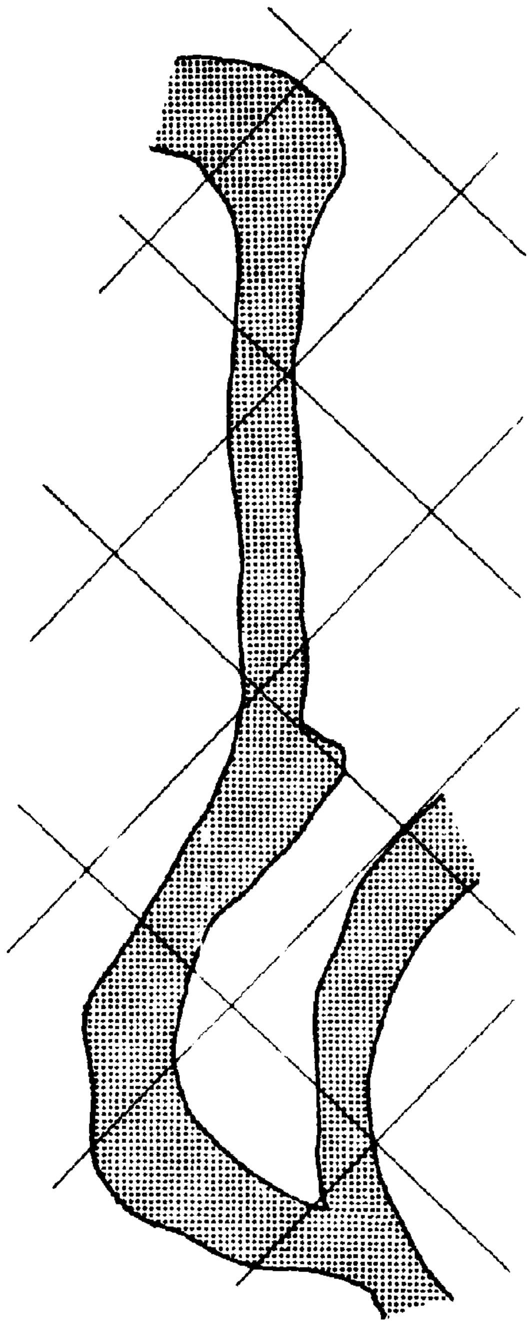
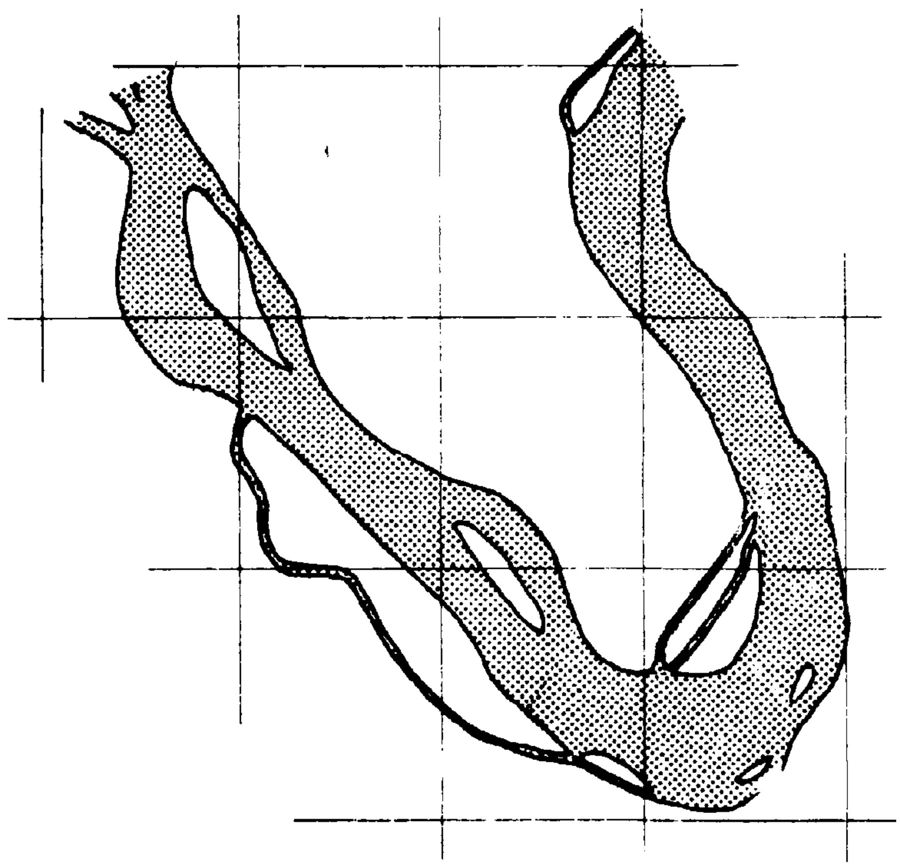
* Transparent overlays for the bank-line maps are in a folder at the end of this report. They have the same page number as the corresponding page in the report.



1880
Mile 0 to Mile 14



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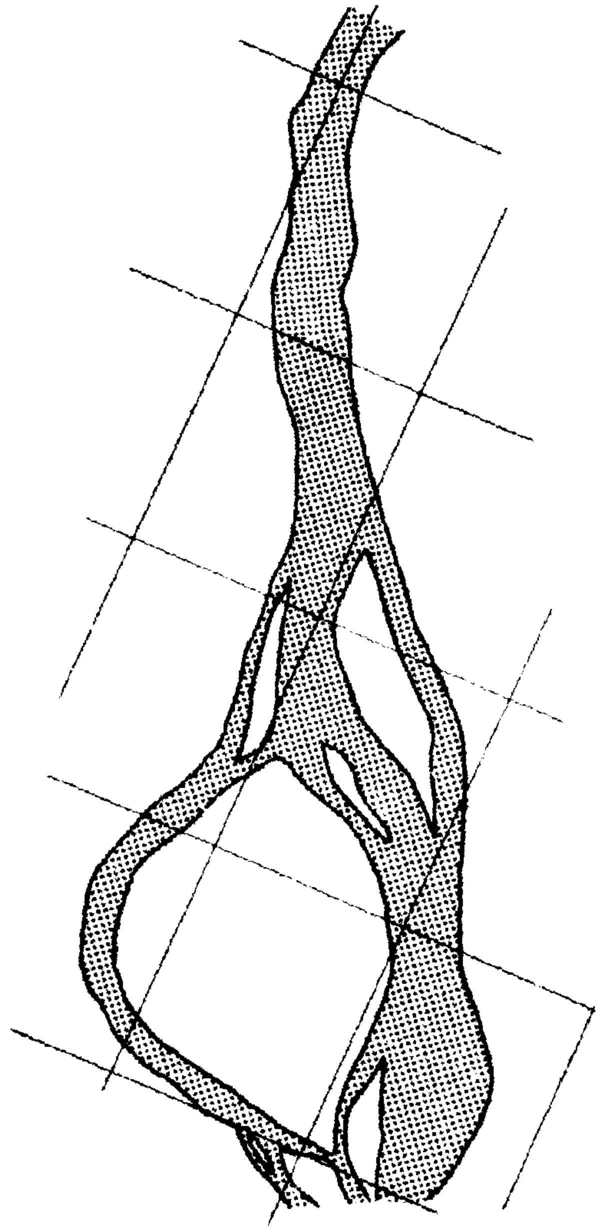
Mile 14 to Mile 34



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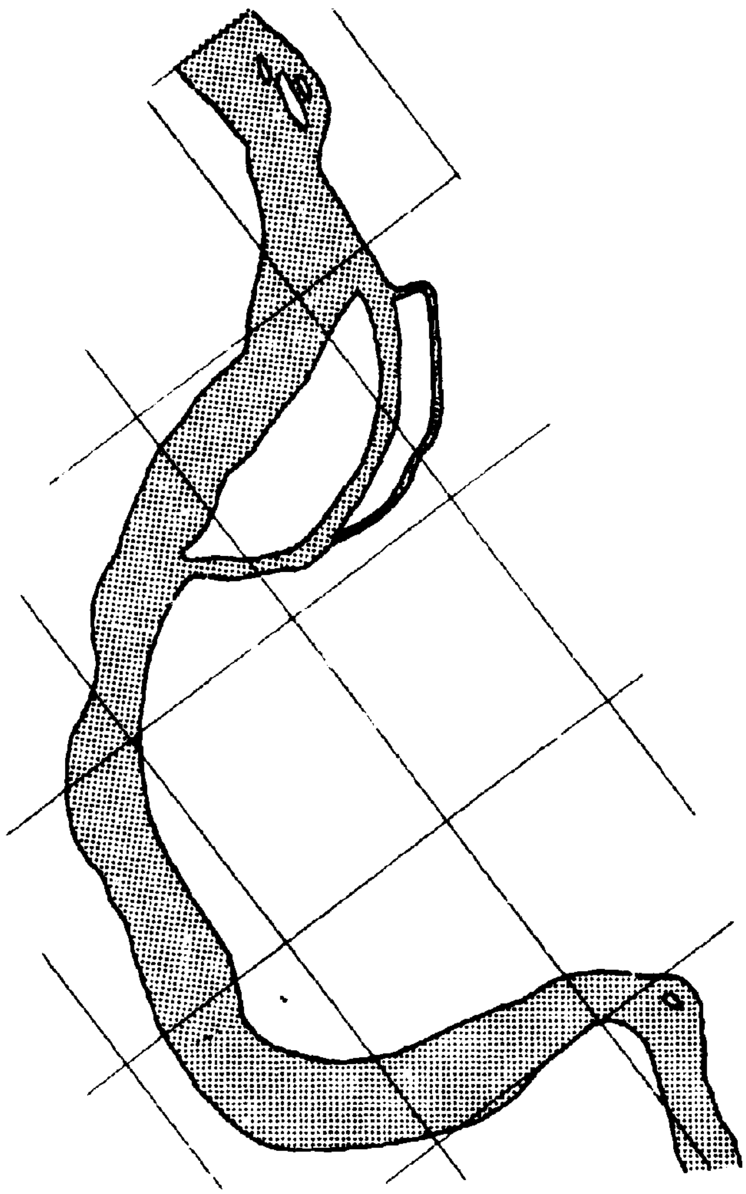
Mile 34 to Mile 44



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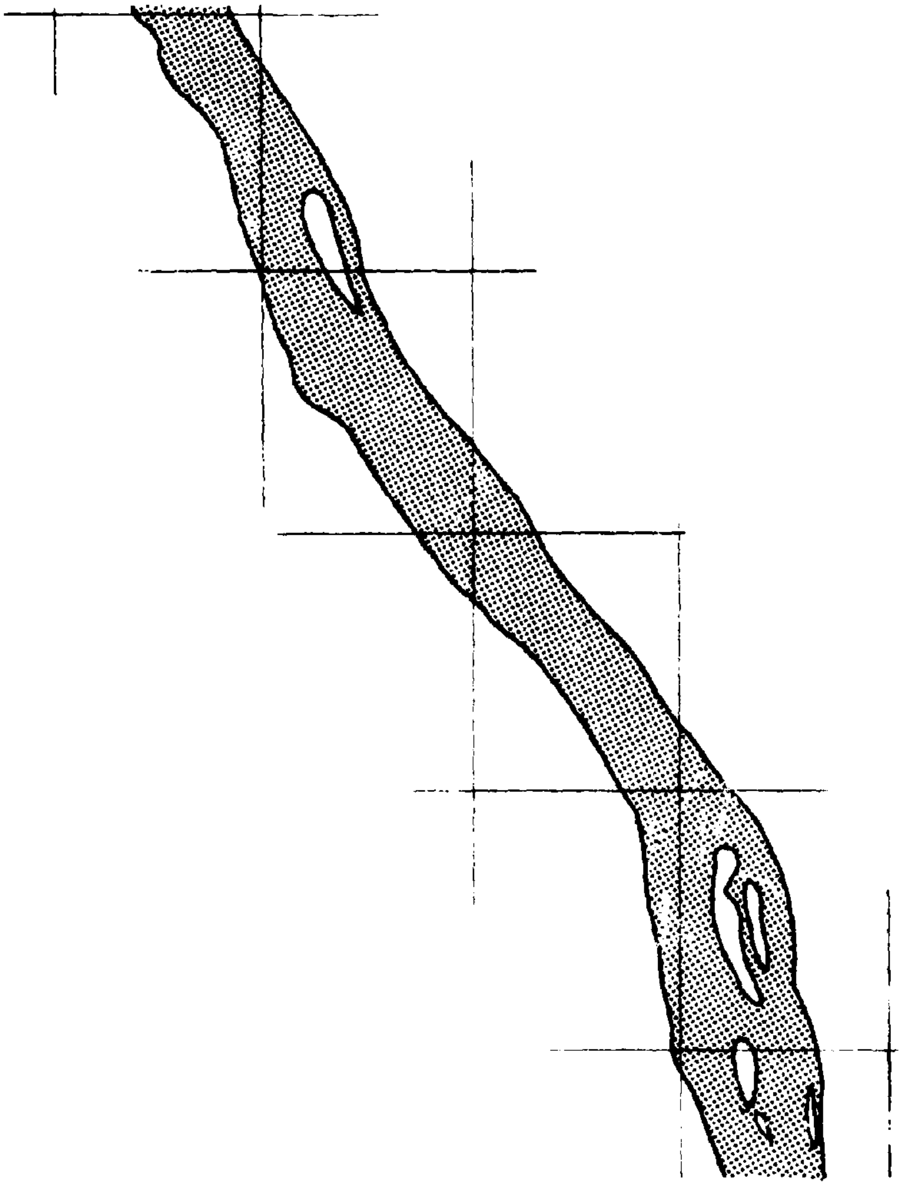

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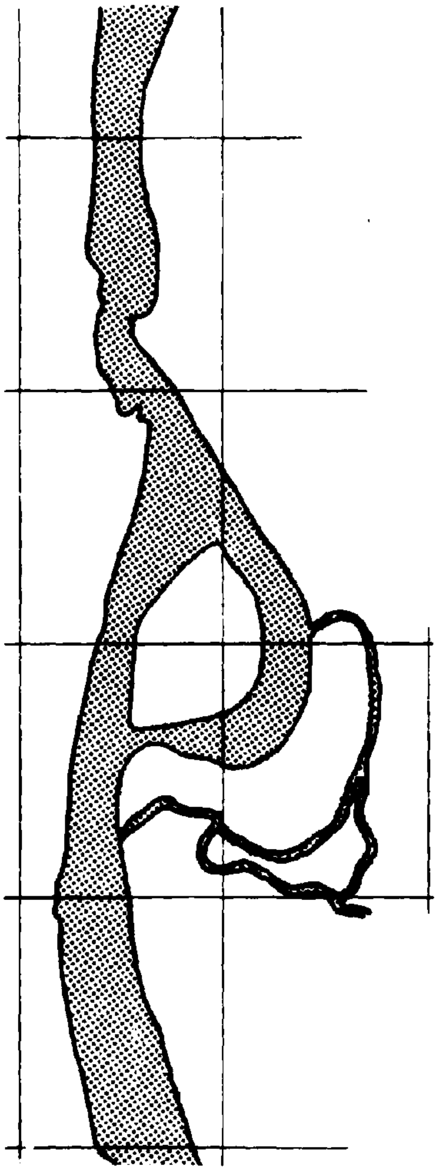
Mile 60 to Mile 73



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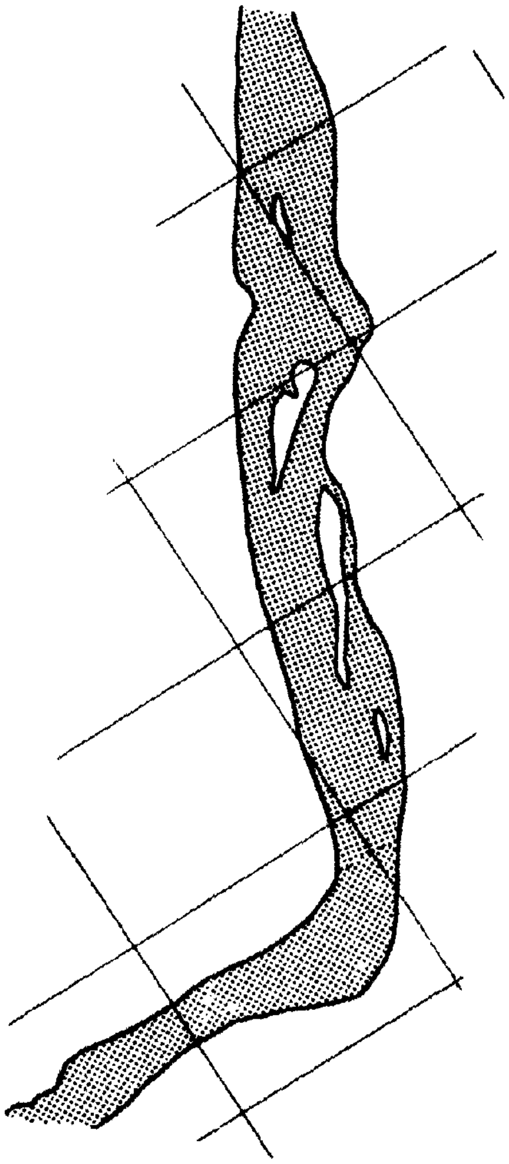
Mile 73 to Mile 84



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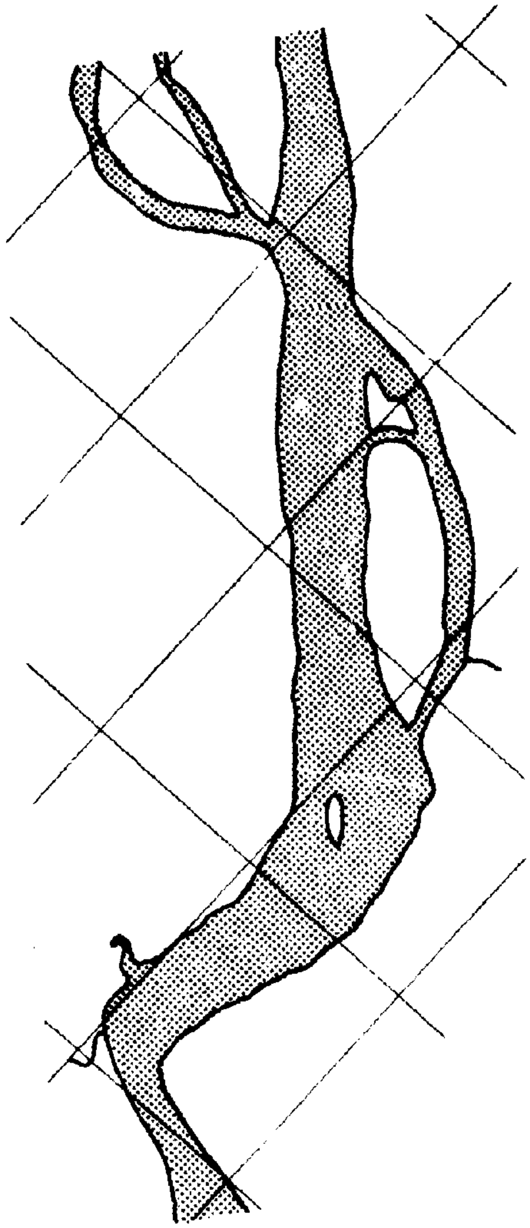
Mile 81 to Mile 94



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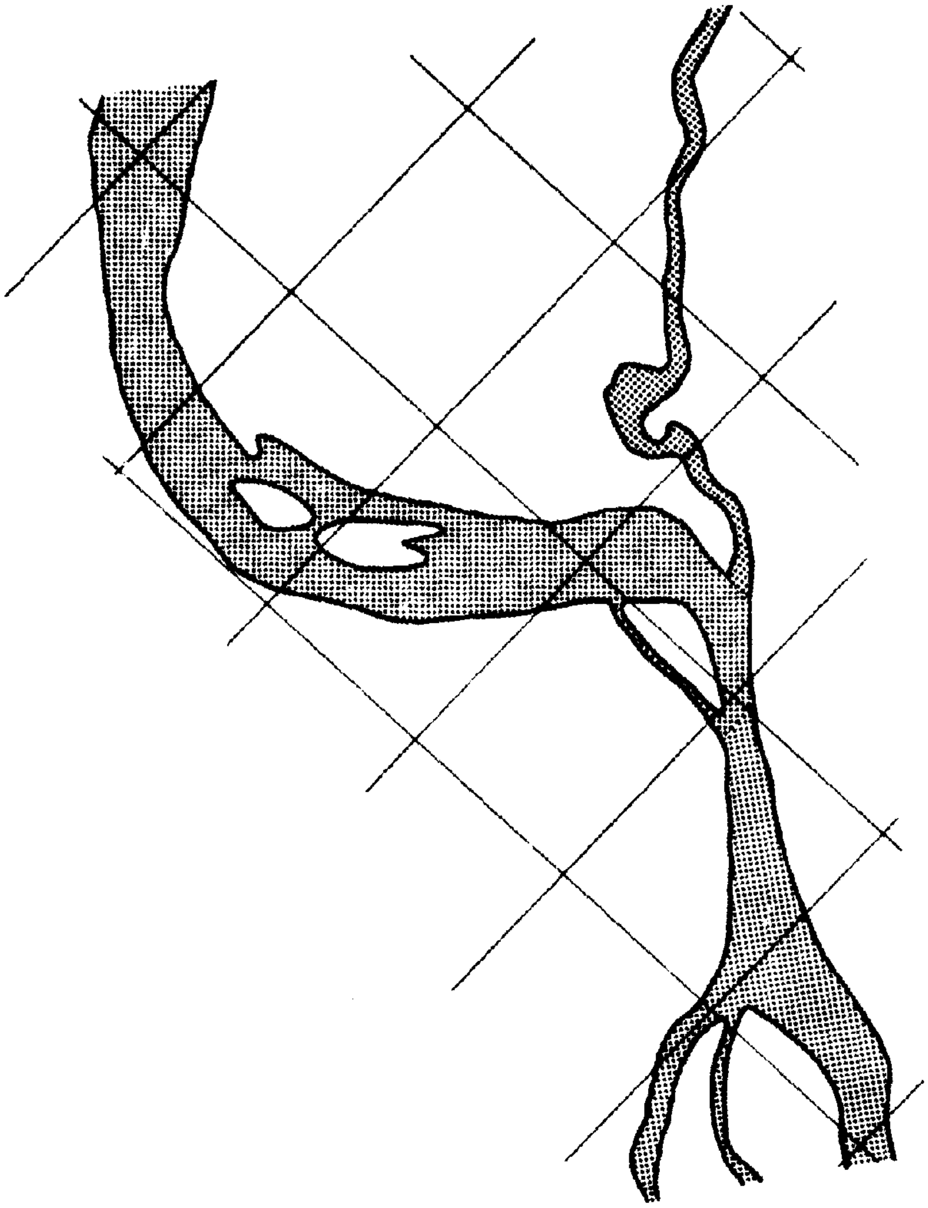
Mile 94 to Mile 105



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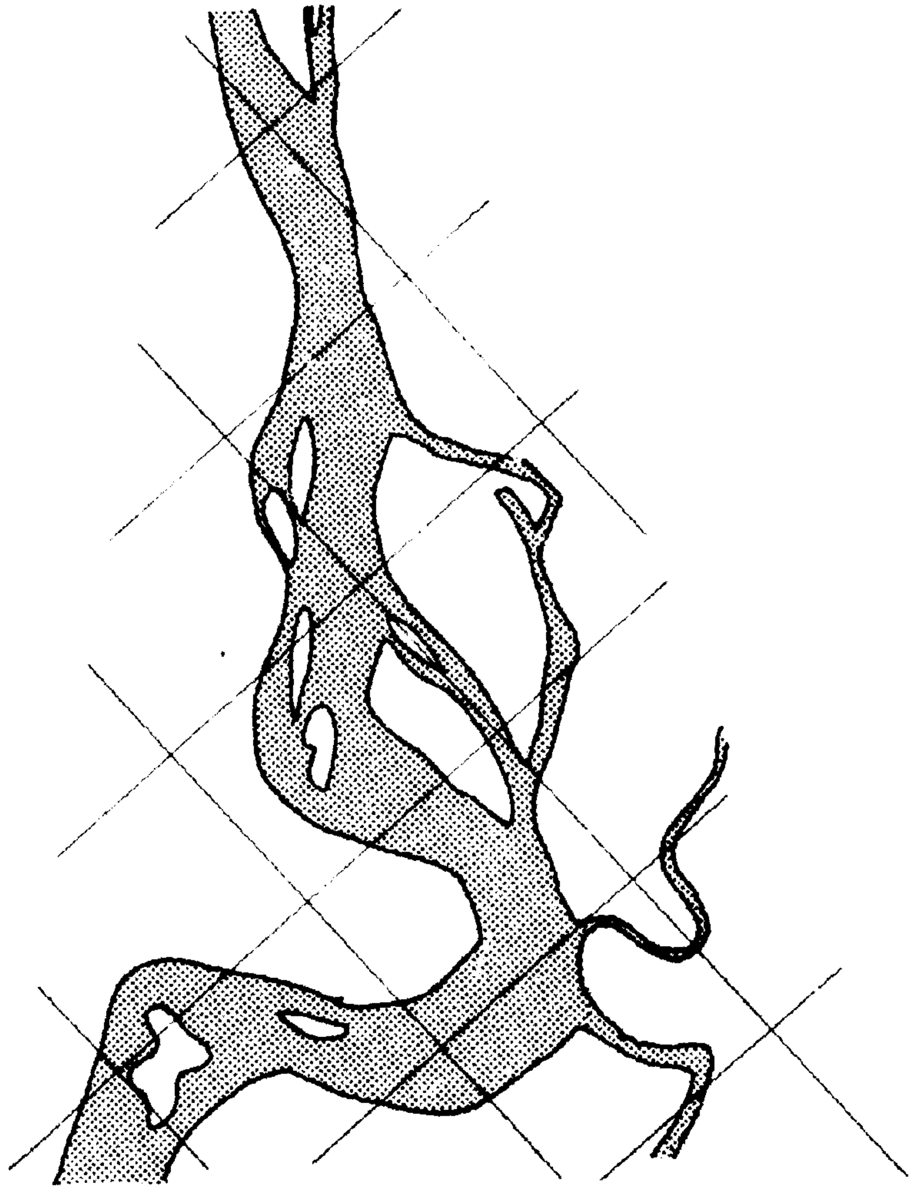
Mile 105 to Mile 116



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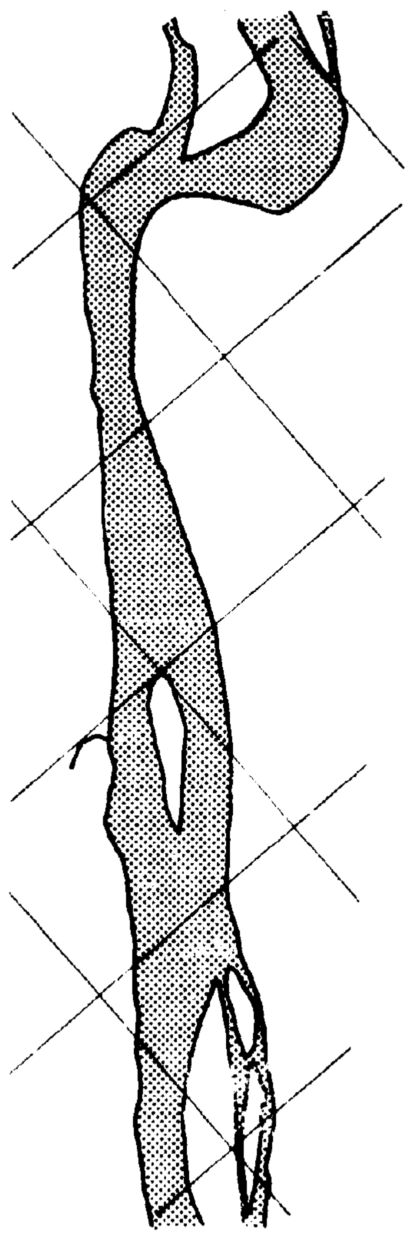
Mile 116 to Mile 127



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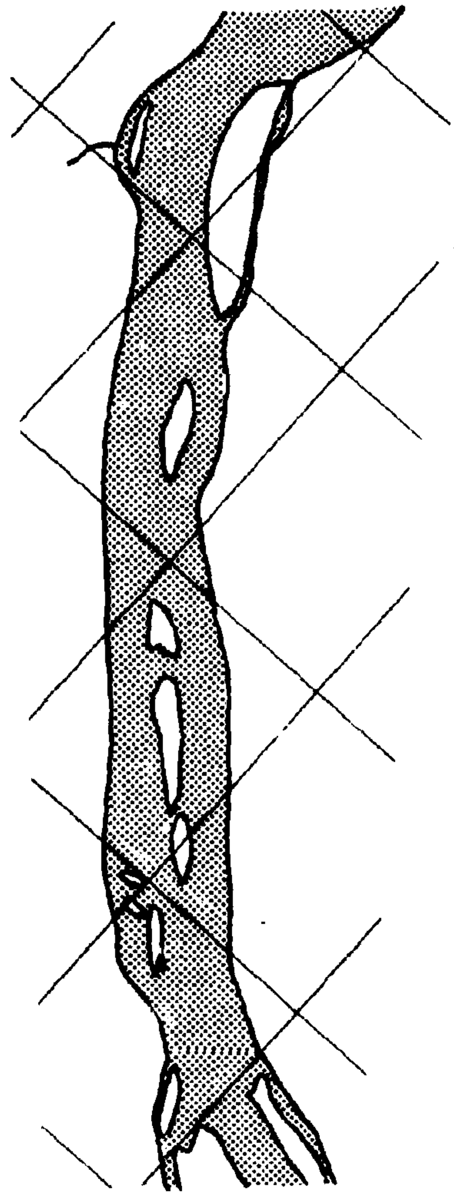

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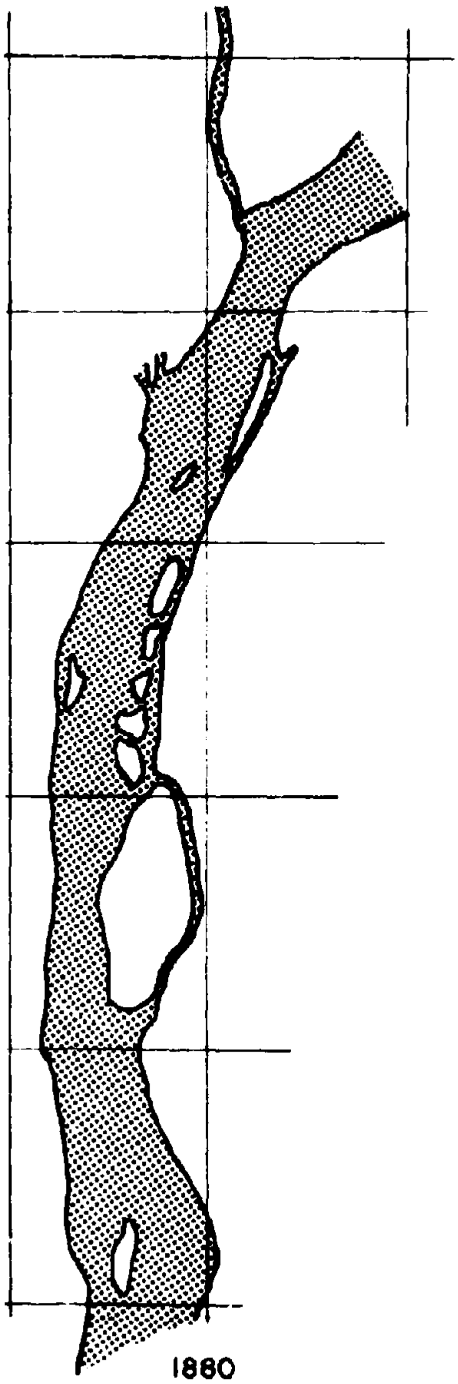
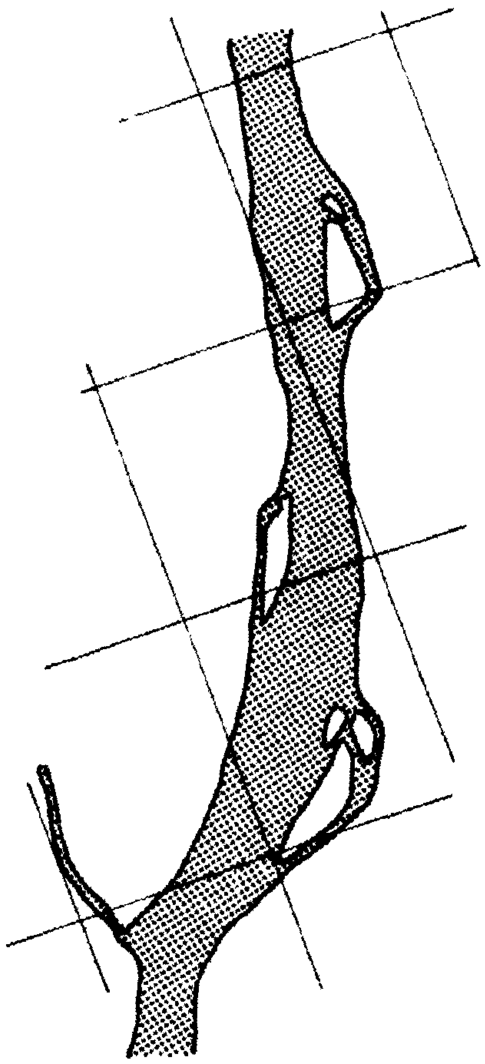


1880
Mile 151 to Mile 162



1880
Mile 162 to Mile 170

APPENDIX B

RIVER BANK LINES IN THE CAPE BEND AND DEVIL'S ISLAND REACHES

The 1810 bank-line map was prepared by Stevens from the original township survey plots. The 1880, 1907, 1927, 1937, 1946, and 1969 bank-line maps* are copies of maps prepared by the Mississippi River Commission or the U.S. Army Engineer District, St. Louis, Corps of Engineers.

Cape Bend is the bend in the lower lefthand side of the maps. The Devil's Island reach is the bend in the upper right-hand side of the maps. The scale of the maps is approximately 1 inch to 8400 feet.

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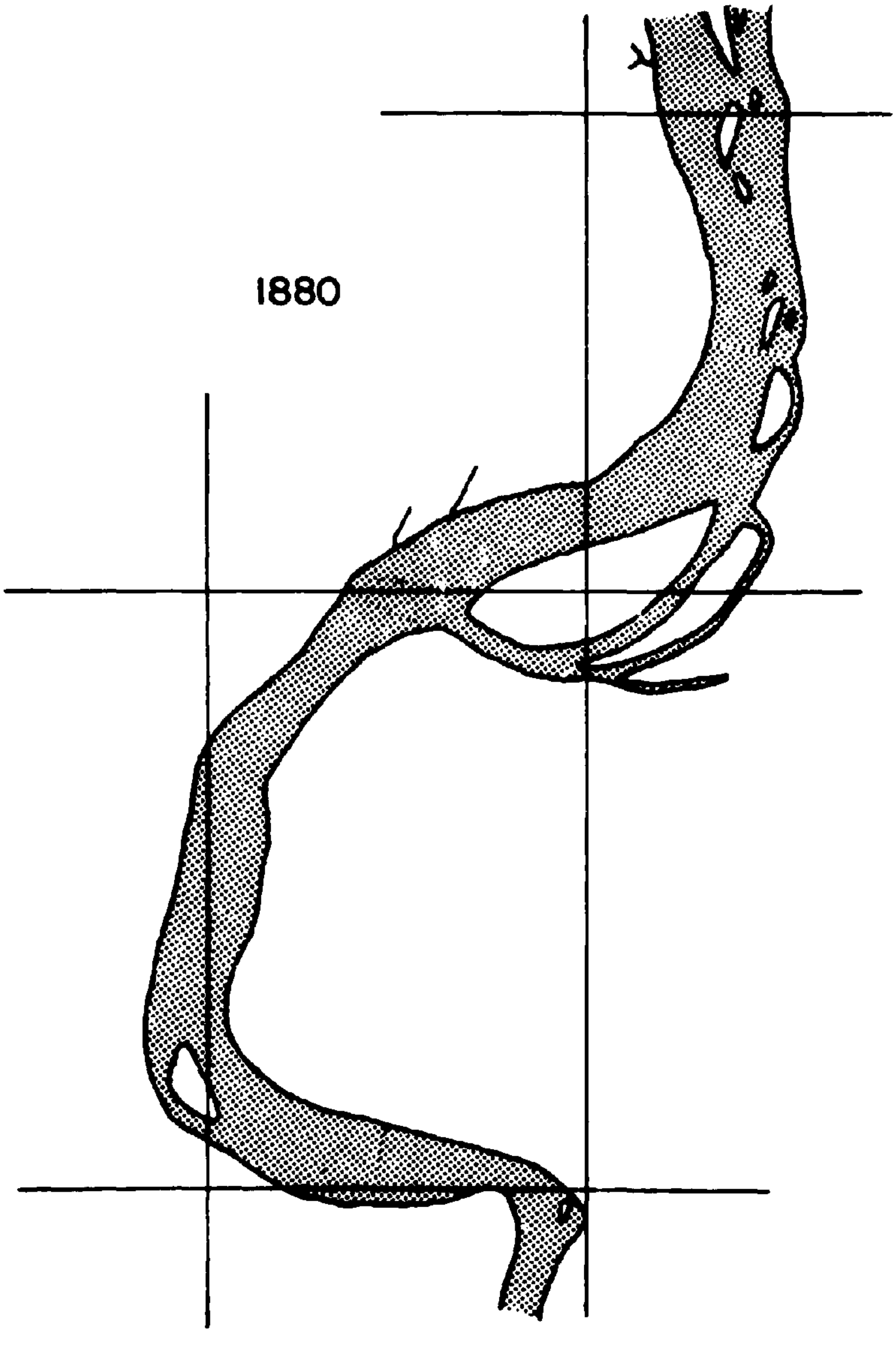
* Transparent overlays for the bank-line maps are in a folder at the end of this report. They have the same page number as the corresponding page in the report.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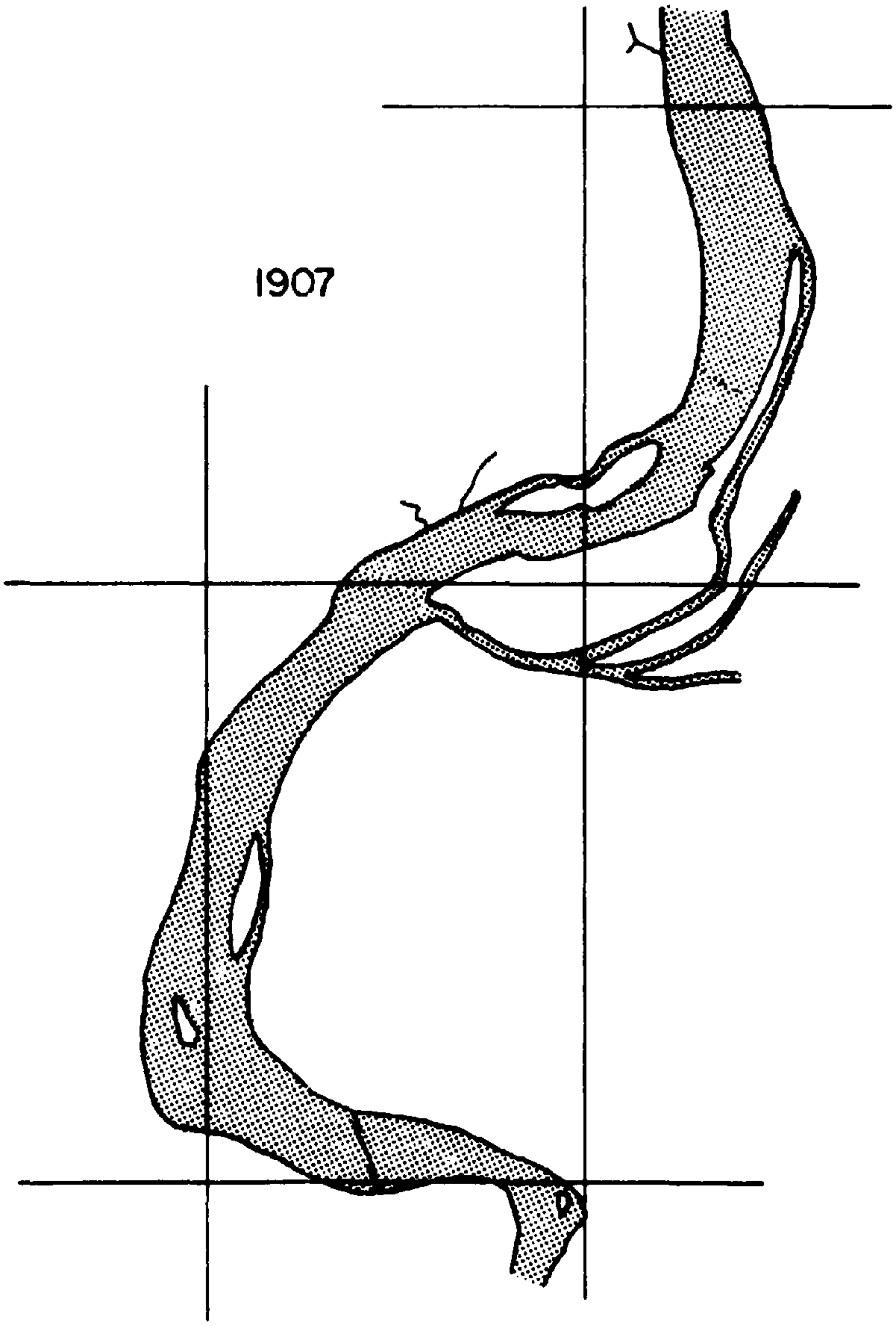
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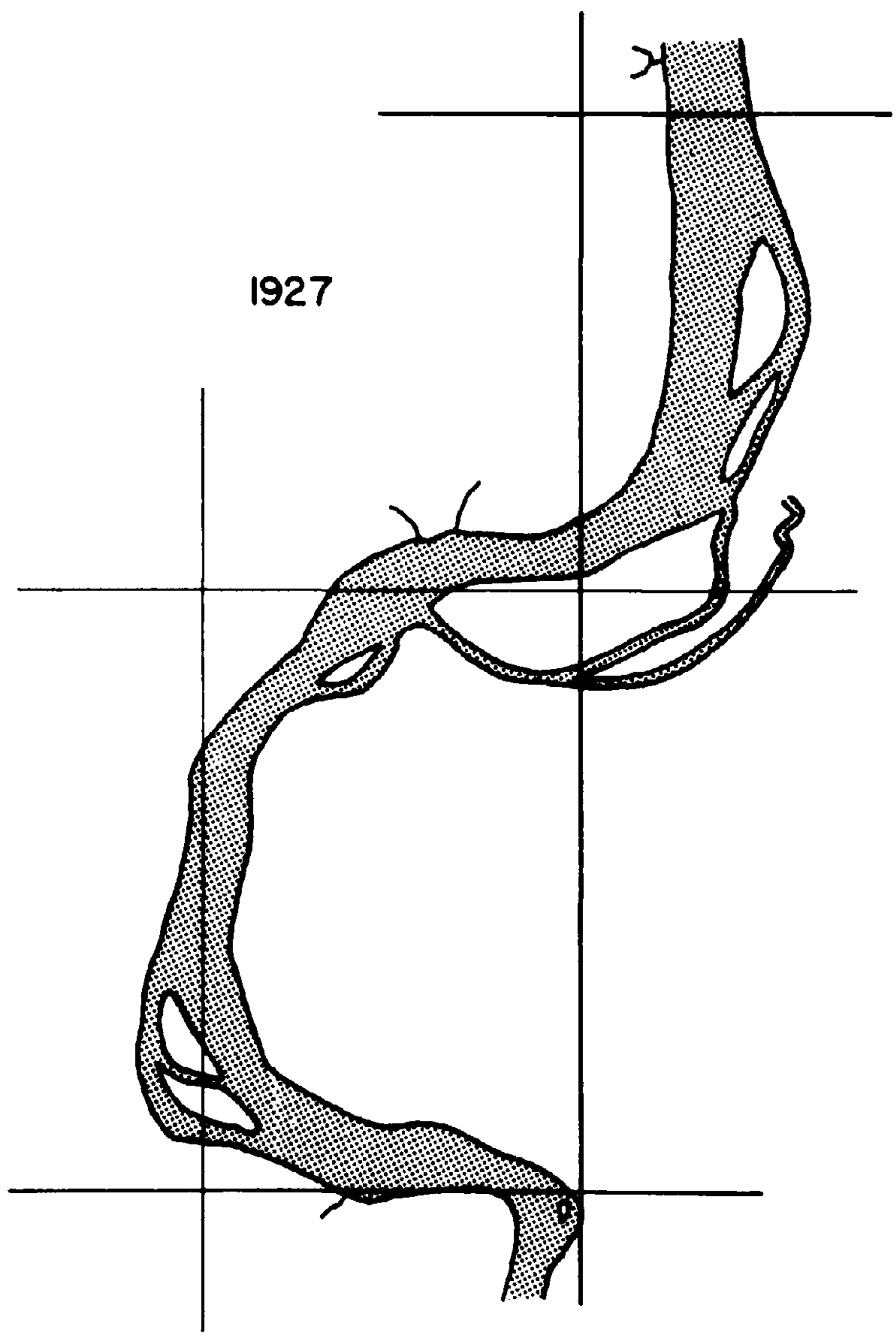
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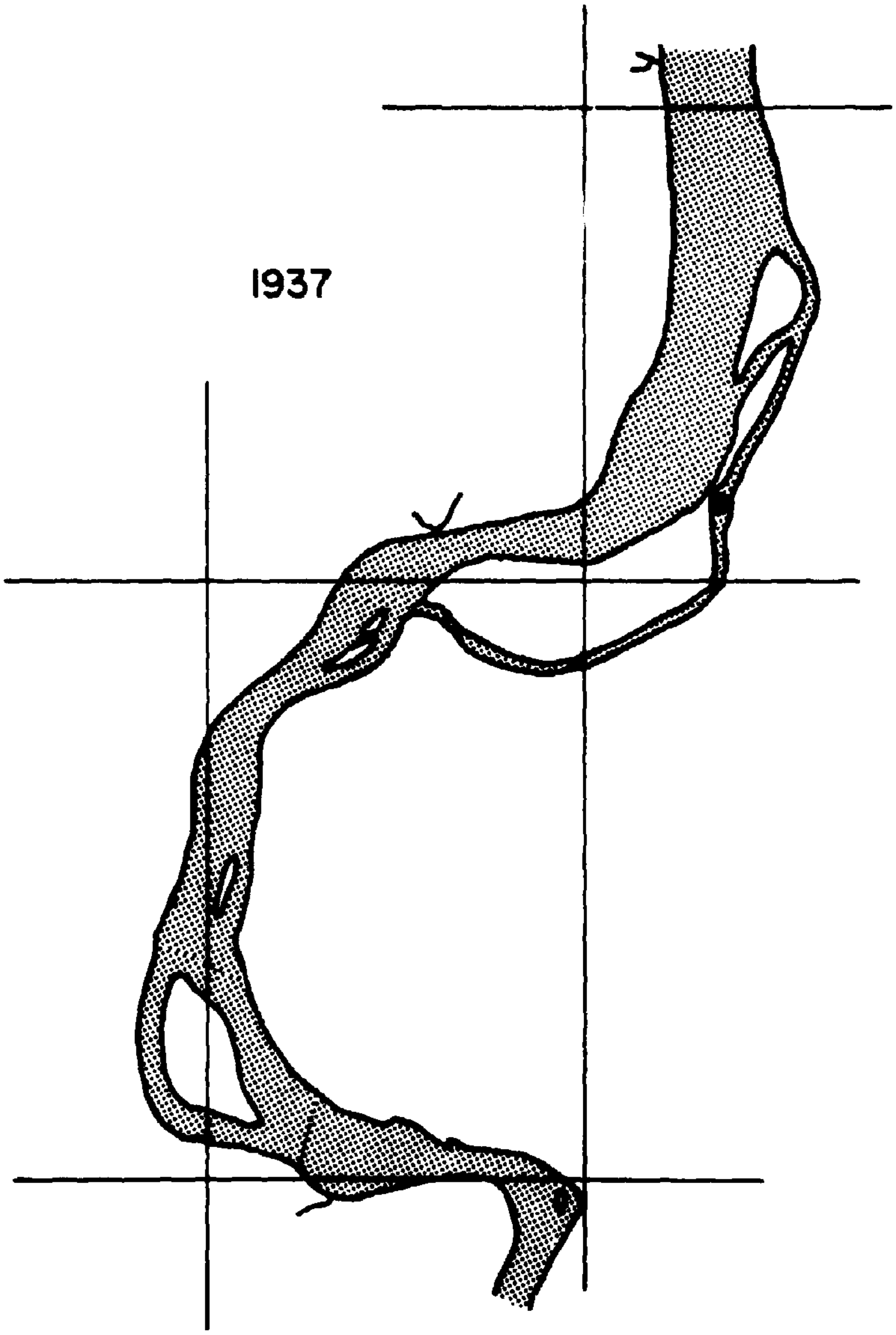
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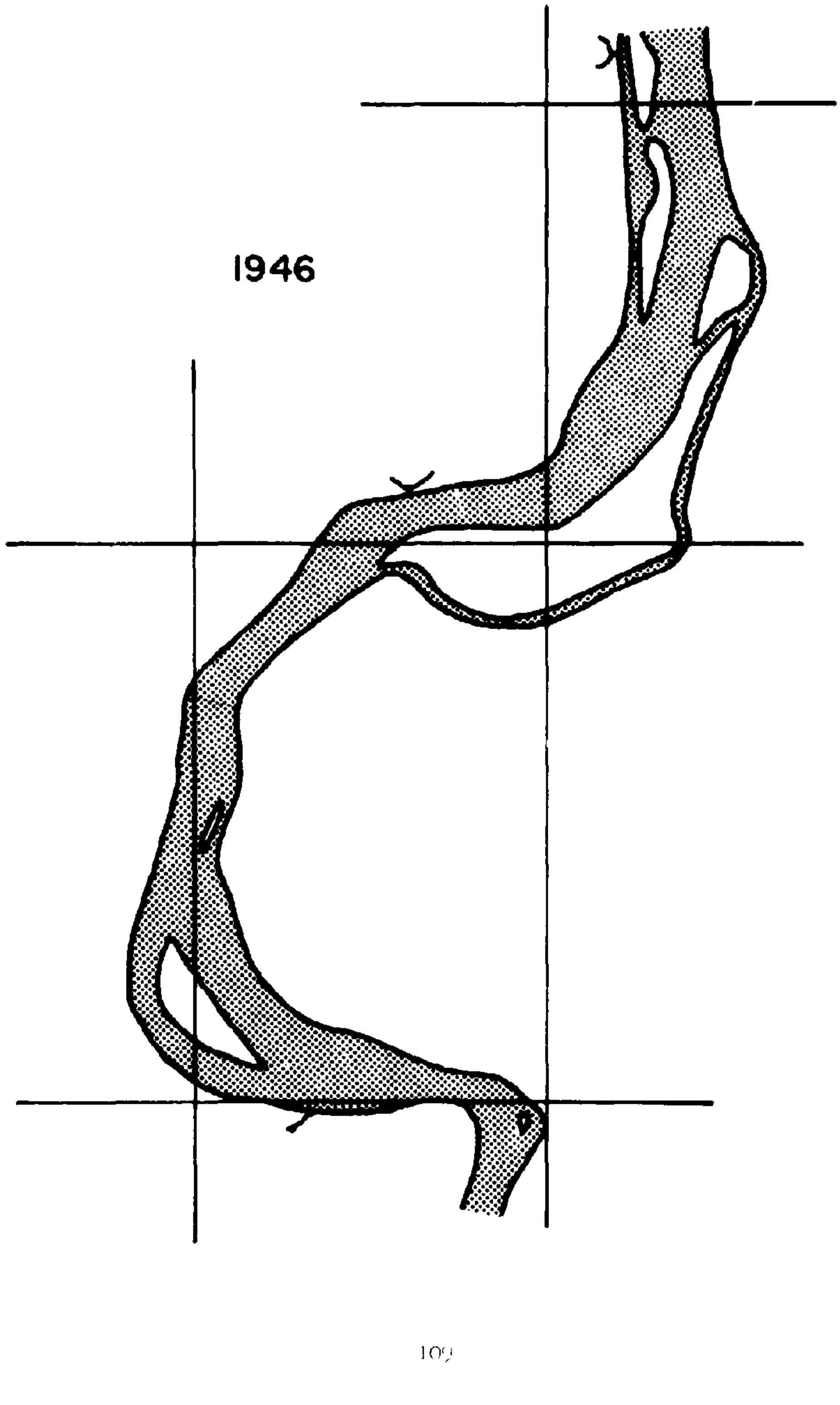
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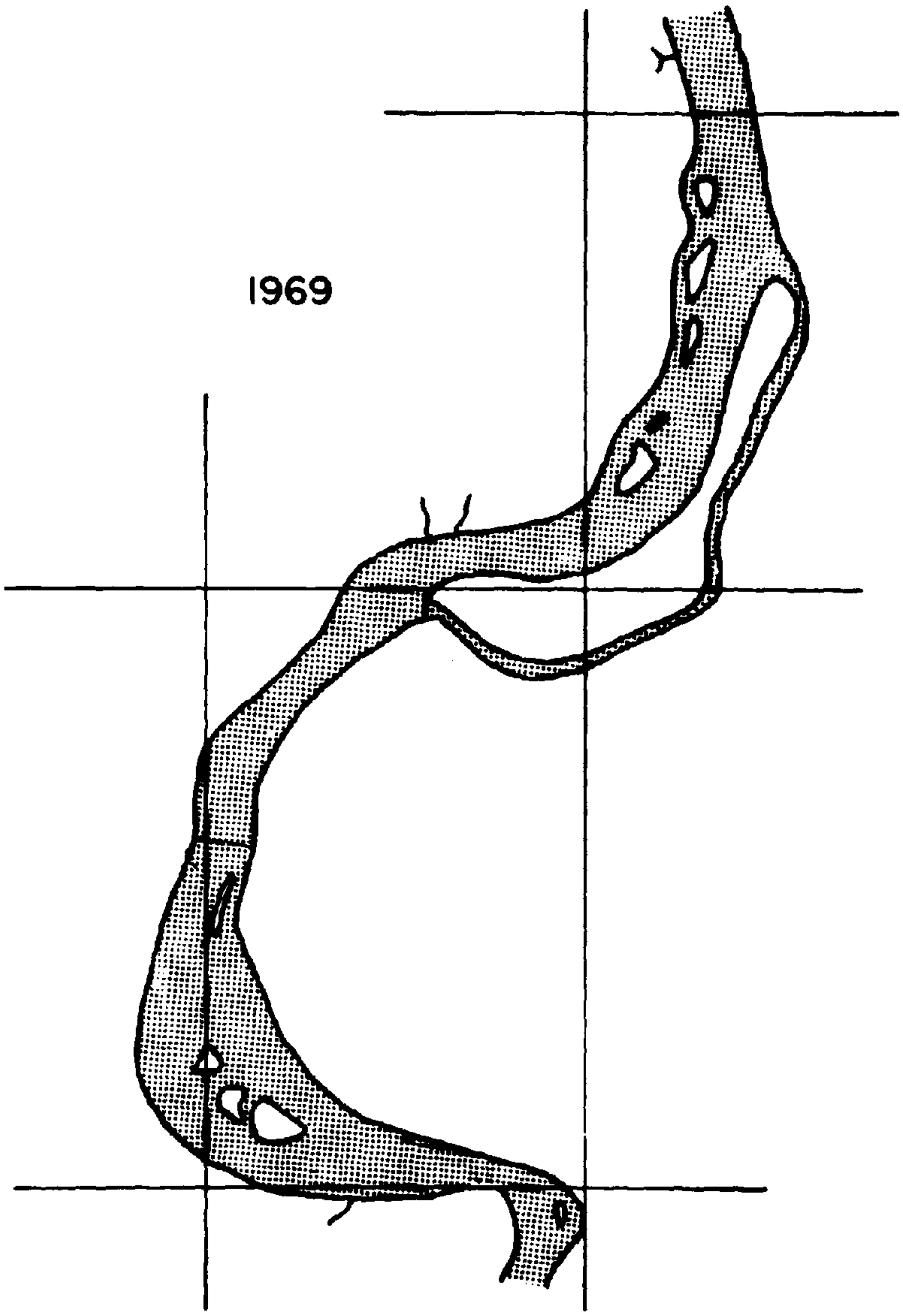
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